EVALUATION OF THREE CLEANING METHODS FOR REMOVING ASBESTOS FROM CARPET

Determination of Airborne Asbestos Concentrations Associated with Each Method

by

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, to measure the impacts, and to search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible, engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report provides information on the effectiveness of three cleaning methods to remove asbestos structures from carpet and the airborne asbestos concentrations associated with the use of each of these methods. Dry vacuuming using vacuum cleaners both with and without a high-efficiency particulate air (HEPA) filter is compared to wet cleaning using a hot-water extraction cleaner without a HEPA filter. This report recommends the use of wet cleaning to remove asbestos from carpets.

E. Timothy Oppelt, Director
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ABSTRACT

This study was conducted to compare the effectiveness of three cleaning methods to remove asbestos from contaminated carpet and to determine the airborne asbestos concentrations associated with the use of each method. The carpet on which the methods were tested was naturally contaminated over a period of approximately 15 to 20 years from fallout of asbestos-containing material in ceiling tiles and fireproofing. Baseline measurements showed an average concentration of 1.6 billion asbestos structures per square foot of carpet. The effectiveness of dry vacuuming using vacuum cleaners with and without a high-efficiency particulate air filter was compared with that of wet cleaning using a hot-water extraction cleaner. Overall, wet cleaning with a hot-water extraction cleaner reduced the level of asbestos contamination in the carpet by approximately 60 percent. No significant evidence was found to indicate either an increase or a decrease in carpet asbestos concentration after dry vacuuming. Airborne asbestos concentrations were approximately 1.3 to 2 times greater during than before the carpet cleaning activities. The type of cleaner used did not greatly affect the difference between the airborne asbestos concentration before and during cleaning. Personal breathing zone concentrations did not exceed the Occupational Health and Safety Administration (OSHA) action level of 0.1 fiber per cubic centimeter of air. A reduction in the amount of asbestos in the carpet would suggest a possible reduction in the potential exposure to custodial workers and building occupants.

International Technology Corporation submitted this document to the U.S. Environmental Protection Agency's Office of Research and Development, Risk Reduction Engineering Laboratory, in fulfillment of Contract No. 68-C0-0016. The report covers the period from March 1991 to March 1992, and work was completed as of March 31, 1992.

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John R. Kominsky, CIH, Ronald W. Freyberg, and Kim A. Brackett, Ph.D., of International Technology Corporation (IT) were the principal authors. Marty Phillips of IT performed the technical edit of the report.

SECTION 1

INTRODUCTION

Asbestos-containing materials (ACM) may release asbestos fibers into the building air as a result of disturbance, damage, or deterioration over time. A concern is the extent to which carpet and furnishings may be reservoirs of asbestos fibers and the release behavior of these fibers when normal custodial cleaning operations are performed.

The Asbestos Hazard Emergency Response Act (AHERA) requires that all carpeting in areas of school buildings in which friable ACM are present be cleaned with either a high-efficiency particulate air (HEPA)-filtered dry vacuum cleaner or a hot-water extraction cleaner ("steam cleaner") without HEPA filtration. Little quantitative information is available on how effectively these two vacuum cleaners remove asbestos fibers from carpet or on the potential for airborne asbestos fibers to become reentrained during these carpet-cleaning activities.

Background

In 1988, the Risk Reduction Engineering Laboratory (RREL) of the U.S. Environmental Protection Agency (EPA) compared the effectiveness of dry vacuuming and wet cleaning for the removal of asbestos fibers from artificially contaminated carpet.[1] In addition, airborne asbestos concentrations were measured during the carpet-cleaning activities. Artificially contaminating the carpet with known levels of asbestos resulted in a carefully controlled experiment with sufficient replication to demonstrate that the wet

cleaning method removed significantly more asbestos material from the carpet than did the dry cleaning method. Both the wet and dry cleaning methods resulted in a significant increase in airborne asbestos concentrations.[2]

In 1990, EPA's RREL conducted a "real-world" study to determine whether the experimental results obtained with artificially contaminated carpet would also apply to carpet naturally contaminated via the release of asbestos fibers from in-place ACM. This study was conducted to compare the effectiveness of three cleaning methods to remove asbestos from naturally contaminated carpet and to determine the airborne asbestos concentrations associated with the use of each of these methods. The carpet on which these methods were tested was naturally contaminated over a period of approximately 15 to 20 years as a result of asbestos-containing material in ceiling tiles and fireproofing on structural members above the ceiling. The effectiveness of dry vacuuming using vacuum cleaners with and without a high-efficiency particulate air (HEPA) filter was compared with that of wet cleaning using a hot-water extraction cleaner without HEPA filtration.

Objectives

The primary objectives of this study were 1) to determine the ability of three cleaning methods to remove asbestos structures from carpet, 2) to determine airborne asbestos levels during carpet cleaning by each of the three cleaning methods, and 3) to compare fiber concentrations measured by phase contrast microscopy during each cleaning method with the Occupational Safety and Health Administration (OSHA) action level of 0.1 fiber per cubic centimeter.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following are the principal conclusions reached during this study:

- The test results demonstrate that dry vacuuming alone is not an effective method for removal of asbestos structures from carpet. The difference between the effectiveness of wet cleaning and dry vacuuming in the removal of asbestos structures from carpet was significant. Wet cleaning reduced the asbestos concentration in the carpet by approximately 60 percent, whereas there was no significant evidence of either an increase or decrease in asbestos concentrations after dry vacuuming.

- The type of cleaning method employed had no significant effect on the difference between airborne asbestos concentrations before and during cleaning. Both wet cleaning and dry vacuuming of carpet resulted in a statistically significant increase in airborne asbestos concentrations in the work area. Airborne asbestos concentrations were 1.3 to 2 times greater during than before the carpet-cleaning activities.

- The results of this study, which represents carpet with natural asbestos contamination and wear characteristics, are comparable with results from a controlled study under artificial, simulated conditions in both efficacy of the carpet cleaning methods and reentrainment of asbestos structures during carpet-cleaning activities.

- Removal of the carpet used in the cleaning experiments resulted in a statistically significant increase in airborne asbestos concentrations in the work area. Airborne asbestos concentrations were 1.7 to 4.3 times greater during than before carpet-removal activities.

- Although the personal breathing zone samples analyzed by phase contrast microscopy (PCM) were all below the OSHA action level of 0.1 fiber per cubic centimeter of air, considerably higher exposures are indicated by the personal breathing zone and work area samples analyzed by transmission electron microscopy (TEM). The results of the two analytical techniques

differ because PCM does not detect the smaller fibers (<5 μm in length and <0.25 μm in width) measured by TEM. The structures observed by TEM analyses were predominantly <5 μm in length; that is, 99.6 and 97.1 percent of the asbestos structures generated during dry and wet carpet-cleaning activities, respectively, were <5 μm in length; and 84 percent of those generated during carpet-removal activities were <5 μm in length.

Recommendations

The study conclusions led to the following recommendations:

- In buildings containing friable asbestos-containing materials (ACM), vacuuming of carpets during routine custodial activities to remove general surface debris should be conducted using dry vacuum cleaners equipped with a high-efficiency particulate air (HEPA) filter. Periodic cleaning of carpets should be conducted to remove asbestos structures using wet cleaning methods (e.g., a hot-water extraction cleaner). If ACM has been released onto a carpeted area during an operations and maintenance (O&M) activity or from fallen surfacing material, the gross debris should be removed with a dry vacuum cleaner equipped with a high-efficiency particulate air (HEPA) filter and then followed by wet cleaning of the carpet.

- Further research is needed to assess the release of asbestos structures from carpet during carpet-removal activities in buildings containing friable ACM. In addition, the research should be directed at evaluating particulate suppression techniques (e.g., spray-applied encapsulants) as well as the extent and impact of residual levels of asbestos structures on the floor after carpet removal.

SECTION 3

STUDY DESIGN

Description of Test Site

This study was conducted in the cafeteria area of the East High Rise Building of the Social Security Administration, Baltimore, Maryland. This area was unoccupied, awaiting the removal of asbestos-containing acoustical ceiling tiles and fireproofing on structural members above the ceiling. The acoustical ceiling tiles contained 1 to 5 percent chrysotile, and the fireproofing contained 35 to 40 percent amosite.

The dining area was carpeted with a 0.25-inch cut pile carpet. The carpet was naturally contaminated over a period of approximately 15 to 20 years from fallout of asbestos-containing material in the ceiling tiles and fireproofing. The carpet was in good condition, i.e., there were no torn or visibly worn areas. There was no record of any asbestos abatement in the cafeteria area before the experiment was conducted.

Figure 1 shows the configuration of the study site. Approximately 3700 ft^2 (58 ft x 64 ft) of the carpeted dining area was isolated as the test area. The perimeter containment walls on the west and south sides were constructed of 2-inch by 4-inch lumber with studs spaced on 24-inch centers. The east and north walls were the exterior walls of the building. The west and south walls and the ceiling were covered with 6-mil polyethylene sheeting to prevent any cross contamination of the area with asbestos. Within the test area, nine equally dimensioned areas (19 ft 4 in. by 21 ft 4 in.), each with approximately 400 ft^2 of carpet,

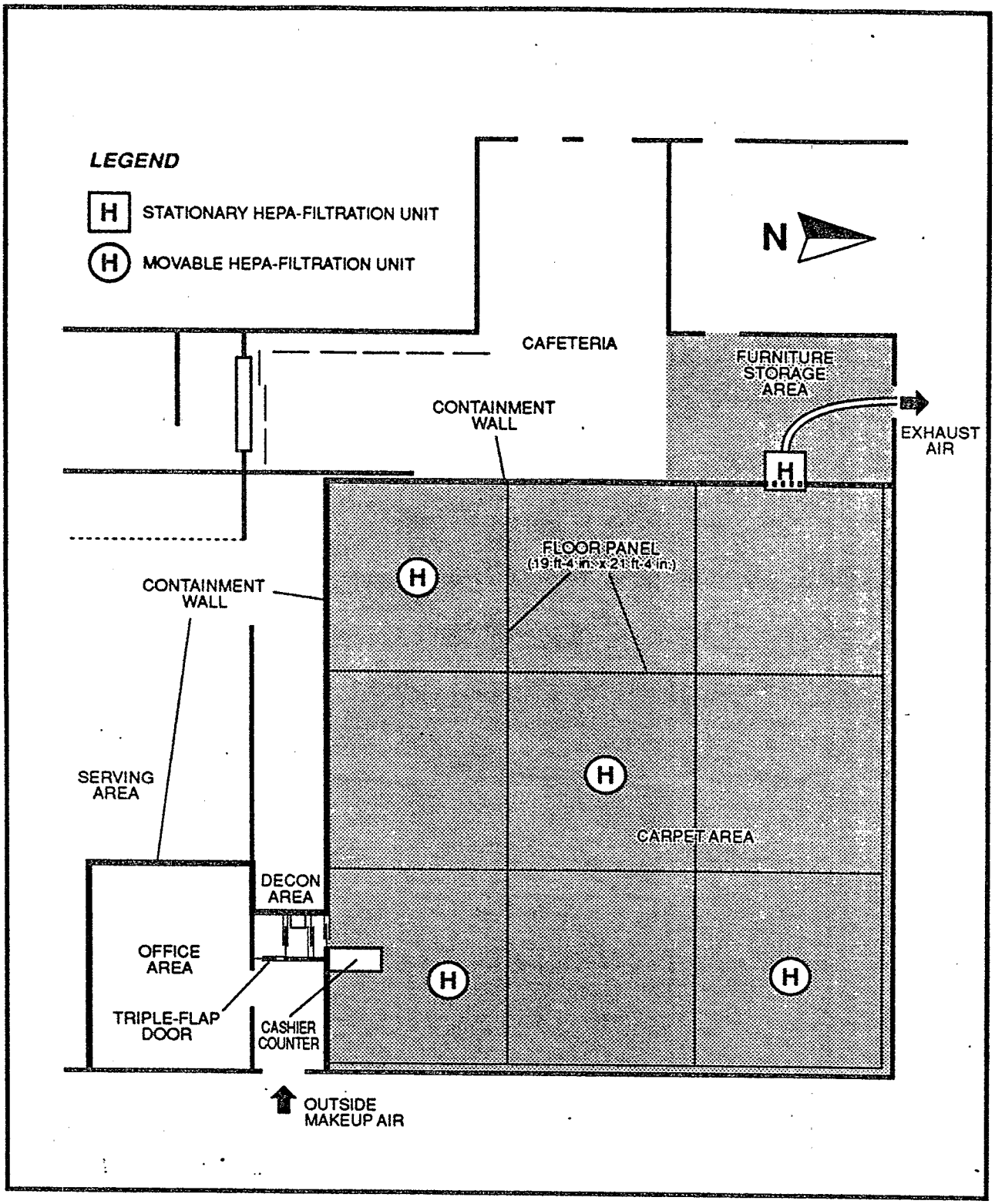

Figure 1. Configuration of the study site.

were defined as experimental test cells. Each test cell was covered by a floor panel 19 ft 4 in. by 21 ft 4 in., which served as a protective barrier against cross contamination during an experiment. The floor panel was removed for each experiment and replaced after the experiment was completed. The floor panel frame was constructed of 2-in. by 4-in lumber, and 6-mil-thick plastic sheeting was stretched across the top surface. An office enclosure (approximately 24 ft by 27 ft) was constructed adjacent to the test area. Entry into the test area was from the office area through a 5-ft by 13-ft decontamination facility. The decontamination enclosure consisted of three equally dimensional chambers: equipment-change room, shower room, and clean room.

Five HEPA filtration units were used to reduce the airborne asbestos concentrations to background levels after each experiment (Figure 1). The units were operated during the preparation phase of the experiment but not during the carpet-cleaning phase. Four of the five HEPA units cleaned and recirculated the air, and the fifth unit discharged the air to the outdoors via flexible ducting. Makeup air to the test area was obtained from outdoors through the door at the decontamination facility.

Experimental Design

Three methods of carpet cleaning were evaluated: 1) dry vacuuming with a HEPA-filtered vacuum cleaner, 2) dry vacuuming with a conventional vacuum cleaner (i.e., without HEPA filtration), and 3) wet cleaning with a hot-water extraction cleaner without HEPA filtration. Each method was tested three times to yield a total of nine experiments. Three different HEPA-filtered vacuums (same model), three different conventional vacuum cleaners

(same model), and three different hot-water extraction cleaners (same model) were used in this study so the results would not be influenced by the pecularities of a single unit.

The carpeted area was divided into nine equal areas, each having approximately 400 ft^2 of carpet. Dividing the carpet into a large number of smaller areas would have made the cleaning process less realistic and prevented collection of a sufficient volume of air for the measurement of airborne asbestos levels. As a means of allowing for possible spatial trends in the contamination level across the carpet, the three cleaning methods were applied according to a 3 x 3 Latin square design. The carpet was divided by a grid of three rows and three columns. Each cleaning method was applied once in each row and each column, which provided three tests of each method (Figure 2).

A single experiment consisted of the following steps:

1) Collecting six baseline work-area air samples prior to the experiment.

2) Collecting six bulk carpet baseline samples from the test area.

3) Dry vacuuming or wet cleaning the carpet for 60 minutes while concurrently collecting a second set of six work-area air samples and three personal breathing zone samples.

4) Collecting a set of six postcleaning bulk carpet samples from the treated area.

5) Dry vacuuming or wet cleaning the carpet a second time for 60 minutes while collecting a second set of three personal breathing zone samples.

6) Collecting a second set of final postcleaning bulk carpet samples from the treated area.

7) Covering the carpet with the protective floor panel.

8) Ventilating the entire experimental room with five HEPA-filtration units for 4 hours.

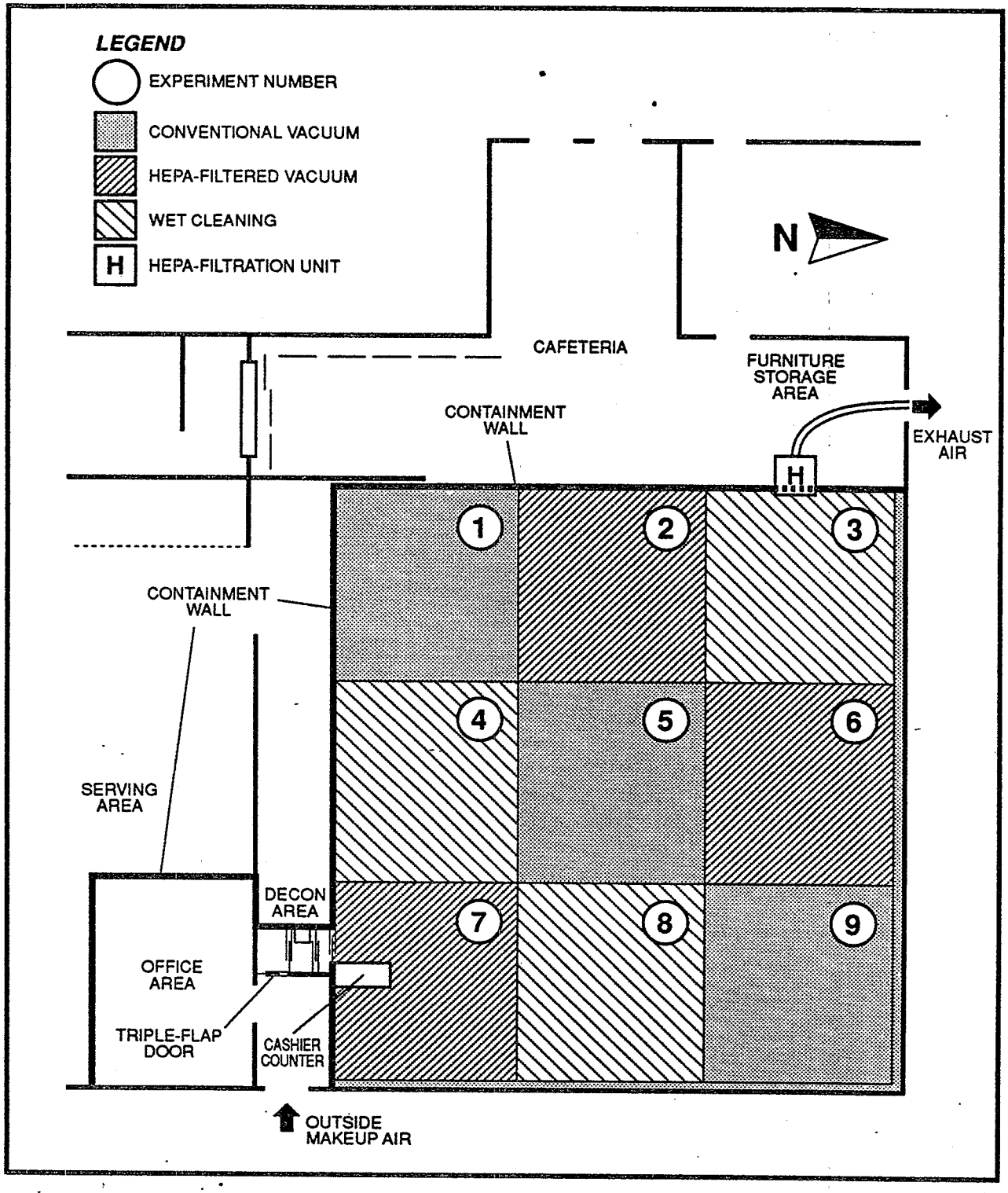

Figure 2. Method & order of cleaning experiments.

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Independence was maintained between all experiments by covering the carpet with nine protective floor panels. The area of carpet to be cleaned was uncovered for each experiment and covered again after the experiment was completed. After each experiment, the entire room was ventilated for 4 hours with five HEPA-filtration units to reduce the airborne asbestos concentrations to baseline or background levels. The five air filtration units were not operated during the baseline air monitoring or during the carpet-cleaning phase of an experiment.

Sampling Strategy

Carpet Samples

Carpet samples were collected before and after cleaning to determine the effectiveness of each cleaning method. Six bulk carpet samples were collected both before and after cleaning by each cleaning method. After the carpet was cleaned a second time, six additional bulk carpet samples were collected. Each test area was divided into approximately four hundred 1-ft^2 areas (a 19-ft by 21-ft grid) by using a string grid system. The carpet was then stratified into three pairs of equally sized sections. One bulk carpet sampling location was selected at random within each of the six sections. This sampling strategy assured the collection of representative samples from the entire piece of carpet.

Air Samples

Area air samples were collected before and during carpet cleaning to evaluate the reentrainment of fibers into the air during carpet-cleaning activities. Six area air samples were collected before and six during the first carpet cleaning by each cleaning method. Area air samples were not collected while the carpet was being cleaned the second time. Two

SECTION 4

MATERIALS AND METHODS

Carpet Cleaning Equipment

Fourteen General Service Administration (GSA) field offices in 11 States were surveyed to identify the most commonly used conventional vacuum cleaner. In 1988, a similar survey of 14 GSA offices and six trade associations was conducted to identify the HEPA-filtered dry vacuum cleaner and hot-water extraction cleaner that were evaluated in the 1988 EPA study.[1,2]

The HEPA-filtered vacuum cleaner used in this study was the same model that was used in the 1988 EPA study. The HEPA-filtered hot-water extraction cleaner used in the 1988 EPA study is no longer being manufactured, and a different cleaner with a HEPA-filtered power head could not be located. Therefore, a hot-water extraction cleaner without HEPA-filtration manufactured by the same company that made the unit used in 1988 was selected. The conventional dry vacuum cleaner selected for this study was the model most frequently mentioned in the GSA survey.

Nilfisk Model GS-80

The HEPA-filtered vacuum cleaner selected for this study was the Nilfisk Model GS-80 manufactured by Nilfisk of America, Inc.. The unit had an airflow capacity of 87 ft^3/min and 75 inches static water lift. (Water lift is the maximum amount of force a vacuum can exert throughout the system if the end of the vacuum hose is completely closed off.) The

unit was also equipped with a 16-inch carpet nozzle with a rotating brush. Three different Nilfisk Model GS-80 vacuum cleaners were used in the study.

Advance AquaClean Model 262500

The hot-water extraction cleaner selected for this study was an AquaClean Model 262500 manufactured by the Advance Machine Company. The unit had an airflow capacity of 95 ft^3/min and static water lift of 117 inches. The cleaner was equipped with a 3-in.-diameter by 14-in.-long motorized agitator brush. This cleaner was not equipped with HEPA filtration. The manufacturer has discontinued manufacturing the AquaClean Model equipped with a HEPA filter.

Hoover Conquest Model U7071

The conventional vacuum cleaner selected in this study was a Hoover Conquest Model U7071, manufactured by the Hoover Company. The unit had an airflow capacity of 110 ft^3 per minute and static water lift of 20 inches. This cleaner was an upright model equipped with a belt-driven agitator brush.

Carpet Cleaning Technique

The carpet in each experiment was methodically vacuumed or wet-cleaned for a period of approximately 60 minutes to allow the collection of a sufficient air volume to obtain an analytical sensitivity of 0.005 s/cm^3. Each of the two cleaning periods consisted of three passes over the carpet with each cleaner. Each pass of the cleaner was at a 90-degree angle to the previous pass.

Sampling Methodology

Carpet Samples

Bulk carpet samples were collected before and after cleaning with a 10-cm (4-in.) square template and a utility razor knife. Each carpet sample was cut in half to provide a duplicate sample for archiving. Each piece of carpet was placed in a separate labeled container. Wide-mouth polyethylene jars with polypropylene screw caps were used to contain the carpet samples. The template and utility razor were thoroughly cleaned between each sample collection to reduce the possibility of cross-sample contamination.

Area Air Samples

The area air samples were collected on open-face, 25-mm-diameter, 0.45-μm-pore-size, mixed cellulose ester (MCE) filters with a 5-μm-pore-size cellulose support pad contained in a three-piece cassette. The filter cassettes were positioned on tripods approximately 5 ft above the floor with the filter face at a 45-degree angle toward the floor. The filter assembly was attached to an electric-powered (110 VAC) 1/6-hp vacuum pump operating at a flow rate of approximately 9 L/min. Air volumes ranged from 487 to 705 L. At the end of the sampling period, the filters were turned upright before being disconnected from the vacuum pump and then stored in this position.

The sampling pumps were calibrated with a precision rotameter (Manostat Model 36-546-215) both before and after sampling. The precision rotameter is a secondary standard; hence, it was calibrated with a primary airflow standard. The quality assurance procedures and quality control checks specified in the AHERA Final Rule (52 CFR 41826, October 30,

1987, pages 41871 through 41880) for sampling operations were adhered to during sample system preparation, sampling, sample recovery, storage, and shipment.

Personal Air Samples

Personal breathing zone air samples were collected on the individual performing the carpet cleaning during each experiment. This individual wore a personal sampling pump with the filter assembly positioned in his/her breathing zone. The samples were collected on open-face, 25-mm-diameter, 0.8-μm-pore-size MCE membrane filters and cellulose support pad contained in a three-piece cassette with a 50-mm conductive cowl. The filter assembly was attached to a constant-flow, battery-powered vacuum pump operating at a flow rate of approximately 2 L/min. The sampling assembly was worn for the duration of the carpet-cleaning activity. Air volumes ranged from 110 to 192 L.

The sampling pumps were calibrated with an electronic mass flowmeter both before and after sampling. The mass flowmeter is a secondary airflow standard; hence, it was calibrated with a primary airflow standard.

Analytical Methodology

Carpet Samples

A sonication procedure was used to extract asbestos structures from the bulk carpet samples for subsequent analysis by TEM. Particles meeting the definition of a fiber length to width aspect ratio $\geq$3:1 and having substantially parallel sides were classified as chrysotile or amphibole in accordance with definitions developed by Yamate.[3] The sonication procedure is presented in detail in Appendix A.

Area Air Samples

The 0.45-μm pore-size MCE filters used to collect the area samples were prepared and analyzed by the EPA TEM laboratory, Cincinnati, Ohio, in accordance with a modified nonmandatory TEM protocol as described in the AHERA Final Rule (40 CFR Part 763, p. 41870). The modifications to the AHERA protocol involve the use of the MCE collapsing method of Burdett and Rood,[4] the recording of the size of all asbestos-containing structures, and the counting criteria as described here. Fibers were sized by measurement of length and width. Bundles were sized by the length of the longest contained fiber and approximate average width if the sides of the bundle were stepped. The aspect ratio of the bundle need not be 5:1 if the fibers composing the bundle meet the 5:1 criterion. Clusters were measured by recording the length and width of the longest asbestos structure within the cluster. Matrices were sized by the length and width of the longest asbestos structure protruding from the matrix. The protruding fiber or bundle was required to have a 5:1 aspect ratio, but the total visible width of the structure was measured even if it was contained within the matrix particle. A sufficient number of grid openings were analyzed to achieve an analytical sensitivity of 0.005 s/cm^3. The minimum area analyzed on high-volume, lightly loaded samples was 0.057 mm^2. Counting was terminated on heavily loaded samples upon finishing the grid opening that contained the 100th asbestos structure.

Personal Air Samples

The 0.8-μm-pore-size MCE filters used to collect the personal breathing zone samples were analyzed in accordance with NIOSH Method 7400 by using phase contrast microscopy at the EPA TEM laboratory. The analytical sensitivity was approximately 0.01 f/cm^3. A

subset of these samples was also analyzed by TEM in accordance with the protocol described for the area air samples.

Statistical Analysis

Carpet Samples

A single estimated concentration for each cleaning method and replicate combination was obtained before and after cleaning by calculating the arithmetic mean of the three individual estimates. This yielded nine pairs of concentrations, three for each cleaning method. The relative change in asbestos concentration was measured by the ratio of the concentration after cleaning to the concentration before cleaning. These ratios were compared by taking the natural logarithm and comparing the averages by standard analysis of variance techniques.

Area Air Samples

The statistical analysis of the area air concentrations was similar to that for the carpet samples. A single estimated concentration for each cleaning method and replicate combination was obtained before and during cleaning by calculating the arithmetic mean of the three individual estimates. The relative change in asbestos concentration was measured by the ratio of the concentration during cleaning to the concentration before cleaning. These ratios were compared by taking the natural logarithm and comparing the averages by standard analysis of variance techniques.

SECTION 5

QUALITY ASSURANCE

The Quality Assurance Project Plan contains complete details of the quality assurance procedures followed during this research project.[5] The procedures used for this study are summarized in the following subsections.

Sample Custody Procedures

Standard sample custody procedures were used to ensure sample traceability. Chain-of-custody procedures document the identity of the sample and its handling from its first existence as a sample until analysis and data reduction are completed. Custody records trace a sample from its collection through all changes of custody until it is transferred to the analytical laboratory. Internal laboratory records then document the custody of the sample through its final disposition.

Each sample was issued a unique project identification number, which was recorded on a sampling data form along with the other information specified on the form. After the labeled sample cassettes were recovered from the sampling trains, the onsite industrial hygienist completed (in ink) a request-for-analysis form and a sample chain-of-custody record. The forms accompanied the samples, and each person having custody of the samples noted receipt of same and completed an appropriate section of the form. Samples were delivered by overnight mail to the analytical laboratory. The laboratory's sample clerk examined the shipping container and each filter cassette for any evidence of damage or

tampering, noted any damage or indication of tampering on the accompanying chain-of-custody form, and then forwarded the form to the IT Project Manager.

Sample Analyses

Specific quality assurance procedures were used to ensure that the laboratory, tools, equipment, sampling media, and reagents were clean and fiber-free. These procedures included the use of filter lot blanks, open and closed field blanks, and laboratory blanks.

Quality control checks were also performed on a routine basis to verify that the analysis system was in control. Routine quality control testing for asbestos focused on precision checks, which involve a second count or multiple counts of a sample or a portion of a sample (i.e., replicate and duplicate sample analyses). Selected samples were also analyzed by a second laboratory.

Lot Blanks

Filter lot blanks, samples selected at random from the lot of filters used in this study, were analyzed to determine background asbestos contamination on the filters. The background asbestos contamination was determined on 5 percent of the total number of 0.45-μm pore-size MCE filters (2000 filters) from the filter lot used in this research study. The filters were prepared and analyzed in accordance with the nonmandatory AHERA TEM method. The TEM analysis of the 100 MCE filters showed a background contamination of 0 asbestos structures per 10 grid openings on each filter.

Field Blanks

Closed field blanks are filter cassettes that have been transported to the sampling site and sent to the laboratory without being opened. Open field blanks are filter cassettes that

have been transported to the sampling site, opened for a short time (<30 s) without any air having passed through the filter, and then sent to the laboratory.

One open and two closed 0.45-μm-pore-size MCE filter field blanks were collected for each of Experiments 1 through 9 and analyzed by TEM. One open field blank was also collected for Experiment 10. No asbestos structures were observed on any of the 19 open field blanks. One asbestos structure was observed on a single closed field blank. No asbestos strucutres were observed on the other eight closed field blanks.

One closed 0.8-μm-pore-size MCE filter field blank was collected for each of Experiments 1 through 11 and analyzed by PCM. Table 1 presents the results of the 11 closed field blank samples.

TABLE 1. CLOSED FIELD BLANKS RESULTS FOR 0.8-μm MCE FILTERS ANALYZED BY PCM

Experiment	Sample number	Total fibers
1	01P-01CB	1
2	02P-01CB	1
3	03P-01CB	1
4	04P-01CB	1
5	05P-01CB	3
6	06P-01CB	0
7	07P-01CB	0
8	08P-01CB	0
9	09P-01CB	0
10	10P-01CB	0.5

Laboratory Blanks

Laboratory blanks are unused filters that are prepared and analyzed in the same manner as samples to verify that the reagents, tools, and equipment are fiber-free and that no

TABLE 2. REPLICATE AND DUPLICATE TEM SAMPLE ANALYSES

	Concentration, s/cm^3		
Sample	Original	Replicate	Duplicate
04A-05B	0.049	0.073	-
07A-05D	0.044	0.073	-
09A-06D	<0.005	<0.005	-
11A-02B	0.036	0.026	-
01A-02B	1.852	-	2.073
11A-02D	0.036	-	0.026

Duplicate Analysis

A duplicate sample analysis was also performed to assess the reproducibilty of the TEM analysis and to quantify the analytical variability due to the filter preparation procedure. A duplicate analysis is the analysis of a second TEM grid prepared from a different area of the sample filter and performed by the same microscopist who performed the original analysis. Two samples were randomly selected for duplicate analysis. The CV associated with these four samples was determined as described for the replicate analyses. The CV for the duplicate sample analyses is 0.17. The results of the original and duplicate analyses are given in Table 2.

Interlaboratory Analysis

Ten air samples were randomly selected and sent to an outside laboratory for quality assurance analysis. The interlaboratory analysis is the preparation and analysis of a TEM grid from a separate area of the sample filter and performed by the outside laboratory. These samples served as a quality control check on the primary laboratory's analysis of the

air samples. The original and second TEM analytical results for these interlaboratory samples are given in Table 3. The coefficient of variation was determined as described for the replicate analyses. The CV for the interlaboratory samples is 0.75. A higher CV for the interlaboratory samples compared with the replicate and duplicate samples is not unexpected because this variability includes that resulting from a different preparation from the filter and from interlaboratory variation.

TABLE 3. INTERLABORATORY TEM SAMPLE ANALYSES ON 0.45-μm MCE FILTERS

	Concentration, s/cm^3	
Sample	Original	Second laboratory
02A-06B	0.121	0.169
03A-03B	0.045	0.138
04A-06B	0.045	0.061
05A-04D	0.067	0.098
05A-05B	0.064	0.028
06A-02D	0.062	0.034
07A-03B	0.035	0.019
08A-04D	0.054	0.065
08A-06B	0.026	<0.005
09A-04D	0.047	0.024

SECTION 6

RESULTS AND DISCUSSION

Fiber Reentrainment

Fixed-Station Area Air Samples

Air sampling results from Experiment 1 (conventional dry vacuum) showed that average airborne asbestos concentrations decreased during the carpet-cleaning activity, whereas all other experiments showed an increase in airborne asbestos levels during cleaning. This anomaly occurred because prior to baseline monitoring in Experiments 2 through 9, the room was ventilated for approximately 4 hours with the five HEPA-filtration units to reduce the airborne asbestos contamination from the previous experiment. The HEPA-filtration units were not operating immediately prior to the baseline monitoring in Experiment 1; therefore, any activity in the room before baseline monitoring began may have contributed to the airborne asbestos levels before the carpet was cleaned. Because the unusually high baseline concentrations are believed to have obscured the effect on airborne fiber reentrainment due specifically to the carpet cleaning activity, the results from Experiment 1 were omitted from further data analysis. (The results of the statistical analysis of these data were essentially unaffected by whether the results from Experiment 1 were or were not included; nevertheless, these data were omitted because of their misleading effect on the summary statistics for the experiments evaluating the conventional vacuum cleaners.)

Individual TEM air sampling results are presented in Appendix B. Table 4 presents the summary statistics separately for concentrations measured before and during the first cleaning stage. Three fixed-station area samples were collected before and during the first cleaning stage in each experiment. This yielded a total of 54 area air samples. For each experiment, a single estimated concentration was then obtained before and during cleaning by taking the arithmetic mean of the three individual estimates. This yielded nine pairs of concentrations, one for each experiment. These concentrations are presented in Appendix C. Figure 3 illustrates the average airborne asbestos concentrations measured before and during the carpet-cleaning activity with each of the three cleaners. An increase in average airborne asbestos concentrations was observed during carpet cleaning with each of the three cleaners. Results from the one-factor analysis of variance are summarized in Table 5. The type of cleaning method had no statistically significant effect on the difference between airborne asbestos concentrations before and during cleaning ($p=0.3127$); that is, the mean relative increase in airborne asbestos concentration during carpet cleaning did not vary significantly with the type of cleaner. The increase in airborne asbestos concentration during the carpet-cleaning activity was statistically significant ($p=0.004$). Specifically, a 95 percent confidence interval for the mean airborne asbestos concentration during carpet cleaning as a proportion of the baseline concentration before cleaning showed that the overall mean airborne asbestos concentration was between 1.3 and 2 times greater during carpet cleaning.

TABLE 4. SUMMARY STATISTICS FOR AREA AIRBORNE ASBESTOS CONCENTRATIONS BEFORE AND DURING CLEANING

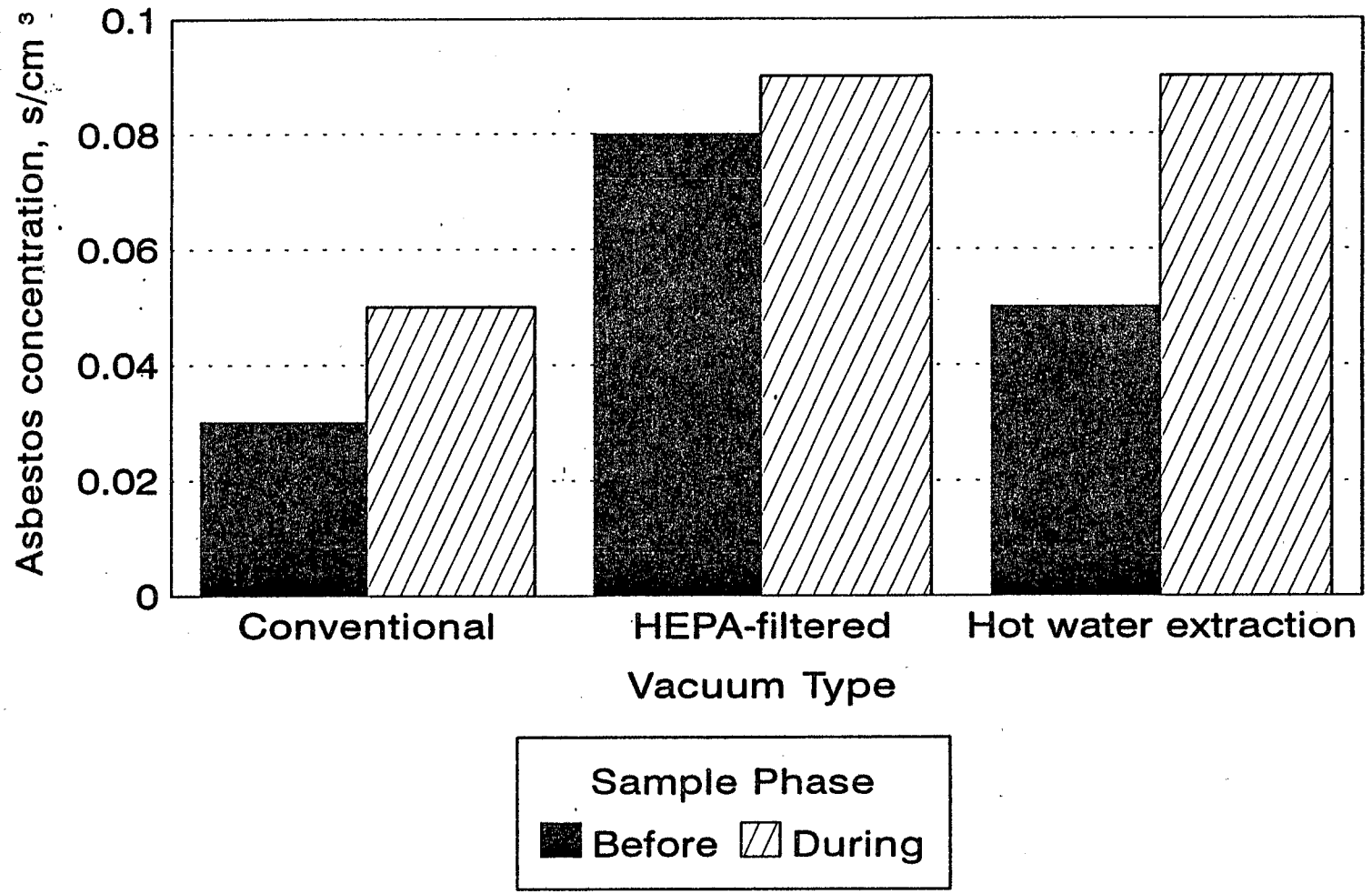
Cleaning method	Number of data points[a,b]	Asbestos concentration, s/cm³ Mean	Minimum	Maximum
Before cleaning				
Conventional dry vacuum	2	0.034	0.053	0.015
HEPA-filtered dry vacuum	3	0.079	0.025	0.163
Hot-water extraction	3	0.046	0.040	0.056
During cleaning				
Conventional dry vacuum	3	0.047	0.030	0.065
HEPA-filtered dry vacuum	3	0.094	0.043	0.168
Hot-water extraction	3	0.093	0.066	0.109

[a]Each data point represents the average of three work-area samples.
[b]Results from Experiment 1 are not included.

TABLE 5. ANALYSIS OF VARIANCE TABLE FOR DIFFERENCE BETWEEN ASBESTOS CONCENTRATIONS BEFORE AND DURING CLEANING

Source of variation	Degrees of freedom	Sum of squares	F-value	p-value
Cleaning method	2	0.2311	1.48	0.3127
Average	1	1.9315	1.93	0.0042
Error	5	0.3903		

These results are consistent with the 1988 EPA research study that evaluated the efficacy of two cleaning methods (HEPA-filtered dry vacuum and HEPA-filtered hot-water extraction cleaner) and the airborne concentrations associated with the use of each cleaner on



Samples were analyzed by transmission electron microscopy

Figure 3. Airborne asbestos concentrations (arithmetic mean) before and during carpet cleaning.

carpet that was artificially contaminated with asbestos.[1,2] The controlled study also showed that the cleaning method had no significant effect on the relative increase in airborne asbestos concentration during cleaning. That study further indicated an overall increase in asbestos concentration that was 2 to 4 times greater during carpet-cleaning activities in comparison with baseline measurements.

Personal Breathing Zone Air Samples

Results of the individual personal breathing zone air samples collected during carpet cleaning are presented in Appendix D. All personal breathing zone samples were analyzed by PCM. Table 6 presents the summary statistics for concentrations measured during carpet cleaning.

TABLE 6. SUMMARY STATISTICS FOR PERSONAL BREATHING ZONE CONCENTRATIONS (ANALYZED BY PCM) DURING CLEANING

Cleaning method	Number of data points[a]	Concentration, f/cm³		
		Mean	Minimum	Maximum
During 1st cleaning				
Conventional dry vacuum	3	0.013	0.005	0.021
HEPA-filtered dry vacuum	3	0.012	0.008	0.018
Hot-water extraction	3	0.013	0.009	0.018
During 2nd cleaning				
Conventional dry vacuum	3	0.011	0.002	0.022
HEPA-filtered dry vacuum	3	0.012	0.006	0.018
Hot-water extraction	3	0.016	0.015	0.019

[a]Each data point represents the average of three samples.

Summary results are presented separately for each of the two cleaning stages. Three personal breathing zone samples were collected during both cleaning stages in an experiment, which yielded a total of 54 personal samples. For each experiment, a single estimated concentration was obtained during the first cleaning and during the second cleaning by taking the arithmetic mean of the three individual sample results from each cleaning. This yielded nine pairs of arithmetic mean concentrations, one for each experiment. These arithmetic mean concentrations are presented in Appendix E. All 54 individual samples showed personal breathing zone concentrations below the OSHA action level of 0.1 f/cm^3. The maximum personal breathing zone concentration was 0.033 f/cm^3. Figure 4 illustrates the average personal breathing zone concentrations measured during the first and second carpet-cleaning stages with each of the three cleaners.

Results from the one-factor analysis of variance are summarized in Table 7. The type of cleaning method had no statistically significant effect on the difference between personal breathing zone concentrations during the first and second cleaning ($p=0.5716$); that is, the mean relative change in personal breathing zone concentration during the first and second carpet cleanings did not vary significantly with the type of cleaner. No statistically significant increase in personal breathing zone concentration occurred during the two carpet-cleaning activities ($p=0.8458$).

TABLE 7. ANALYSIS OF VARIANCE TABLE FOR DIFFERENCE BETWEEN PERSONAL BREATHING ZONE CONCENTRATIONS DURING CLEANING

Source of variation	Degrees of freedom	Sum of squares	F-value	p-value
Cleaning method	2	0.2184	0.61	0.5716
Average	1	0.0073	0.04	0.8458
Error	6	1.0656		

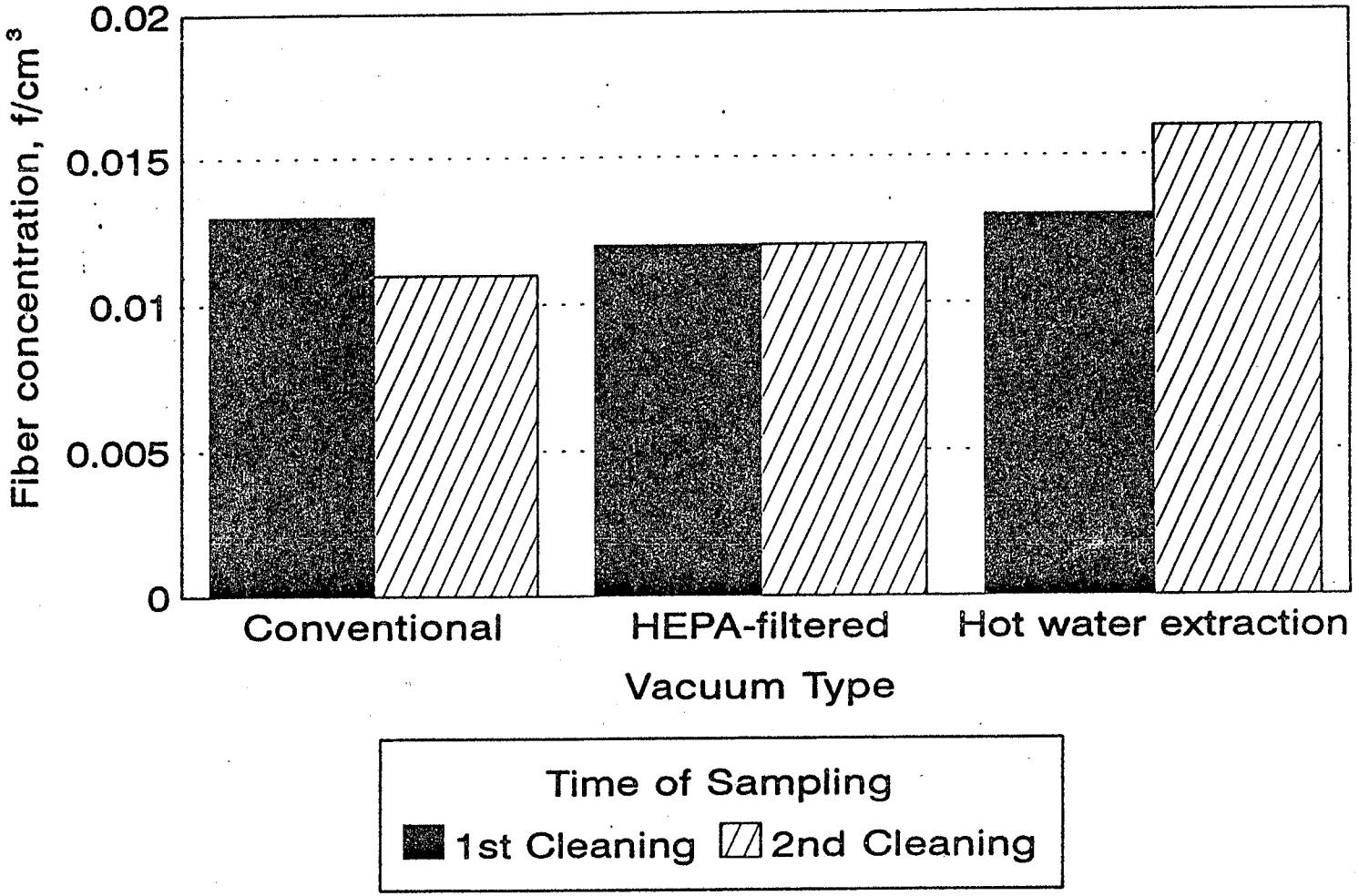


Figure 4. Personal breathing zone concentrations (arithmetic mean) during carpet cleaning.

Thirteen of the 54 personal breathing zone samples were also analyzed by TEM. These samples were selected to represent those with the highest fiber concentration measured by PCM. The concentrations determined by both PCM and TEM are presented in Table 8. Overall, the asbestos concentrations determined by TEM were consistently higher than the total fiber concentrations determined by PCM. This result is not unexpected given the inability of PCM to detect fibers less the 5 μm in length and less than 0.25 μm in width. TEM analysis can measure structures 0.5 μm in length and 0.15 μm in width. The majority of structures observed by TEM analysis were less than 2 μm in length. The Pearson correlation coefficient associated with these measurements ($r=0.03$) indicates no significant linear relationship between these TEM and PCM concentrations.

TABLE 8. COMPARISON OF PERSONAL BREATHING ZONE CONCENTRATIONS MEASURED BY TEM AND PCM DURING CARPET CLEANING

	Concentration	
Sample number	PCM, f/cm^3	TEM, s/cm^3
01P-01D	0.016	0.640
02P-01D	0.017	0.124
02P-01RD	0	0
03P-03D	0.021	0.117
03P-01CB[a]	0 fibers	0 structures
04P-03D	0.013	0.093
05P-03D	0	0.025
06P-03RD	0.015	0.010
08P-03D	0.005	0.034
09P-02RD	0.024	0.040
10P-01D	0.033	0.061
10P-01CB[a]	0 fibers	0 structures
11P-04D	0.061	0.050

[a]Closed field blank.

Carpet Removal

After completing the nine designed experiments to determine the efficacy of the three cleaning methods and the airborne asbestos concentrations associated with the use of each method, the carpet was removed from the floor and rolled up for disposal. Two areas of contaminated carpet were removed. The first area was located outside the contained test area in the furniture storage area (Figure 1). The second area was the entire contained test area (Figure 1).

Furniture Storage Area--Before the carpet was removed from the floor, six baseline, fixed-station, area air samples were collected. During the actual removal of the carpet from the floor, six fixed-station, area air samples and two personal breathing zone samples were collected. All area air samples were analyzed by TEM; both personal breathing zone samples were analyzed by PCM and one was also analyzed by TEM. The air monitoring activity during the carpet removal in the furniture storage area is referred to as Experiment 10.

Contained Test Area--The carpeted area used during the first nine experiments (i.e., carpet-cleaning experiments) was also removed from the floor and rolled up. Before the carpet was removed from the floor, six baseline, fixed-station, area air samples were collected. During the actual removal of the carpet from the floor, six fixed-station, area air samples and six personal breathing zone samples (three samples on each of two persons) were collected. All area air samples were analyzed by TEM; all six personal breathing zone samples were analyzed by PCM and one was also analyzed by TEM. The air monitoring activity during the carpet removal in the contained test area is referred to as Experiment 11.

Tables 9 and 10 present the summary statistics for the area and personal breathing zone concentrations, respectively. Figure 5 presents the average airborne asbestos concentrations during Experiments 10 and 11. The individual results for the area and personal breathing zone samples are presented in Appendices F and G, respectively.

TABLE 9. SUMMARY STATISTICS FOR AREA AIR CONCENTRATIONS OF ASBESTOS (DETERMINED BY TEM) BEFORE AND DURING CARPET REMOVAL

Carpet location	Sample period	N	Concentration, s/cm^3 Mean	Minimum	Maximum
Furniture storage area	Baseline	6	0.056	0.030	0.075
	During removal	6	0.079	0.051	0.106
Contained test area	Baseline	6	0.035	0.015	0.053
	During removal	6	0.093	0.073	0.155

TABLE 10. SUMMARY STATISTICS FOR PERSONAL BREATHING ZONE CONCENTRATIONS OF TOTAL FIBERS (DETERMINED BY PCM) DURING CARPET REMOVAL

Carpet location	N	Concentration, f/cm^3 Mean	Minimum	Maximum
Furniture storage area	2	0.046	0.033	0.059
Contained test area	6	0.069	0.045	0.091

During the carpet-removal activities in the furniture storage area, the average airborne asbestos concentration increased slightly; however, this increase was not statistically significant ($p=0.06$). The personal breathing zone concentrations were below the OSHA action level of 0.1 f/cm^3.

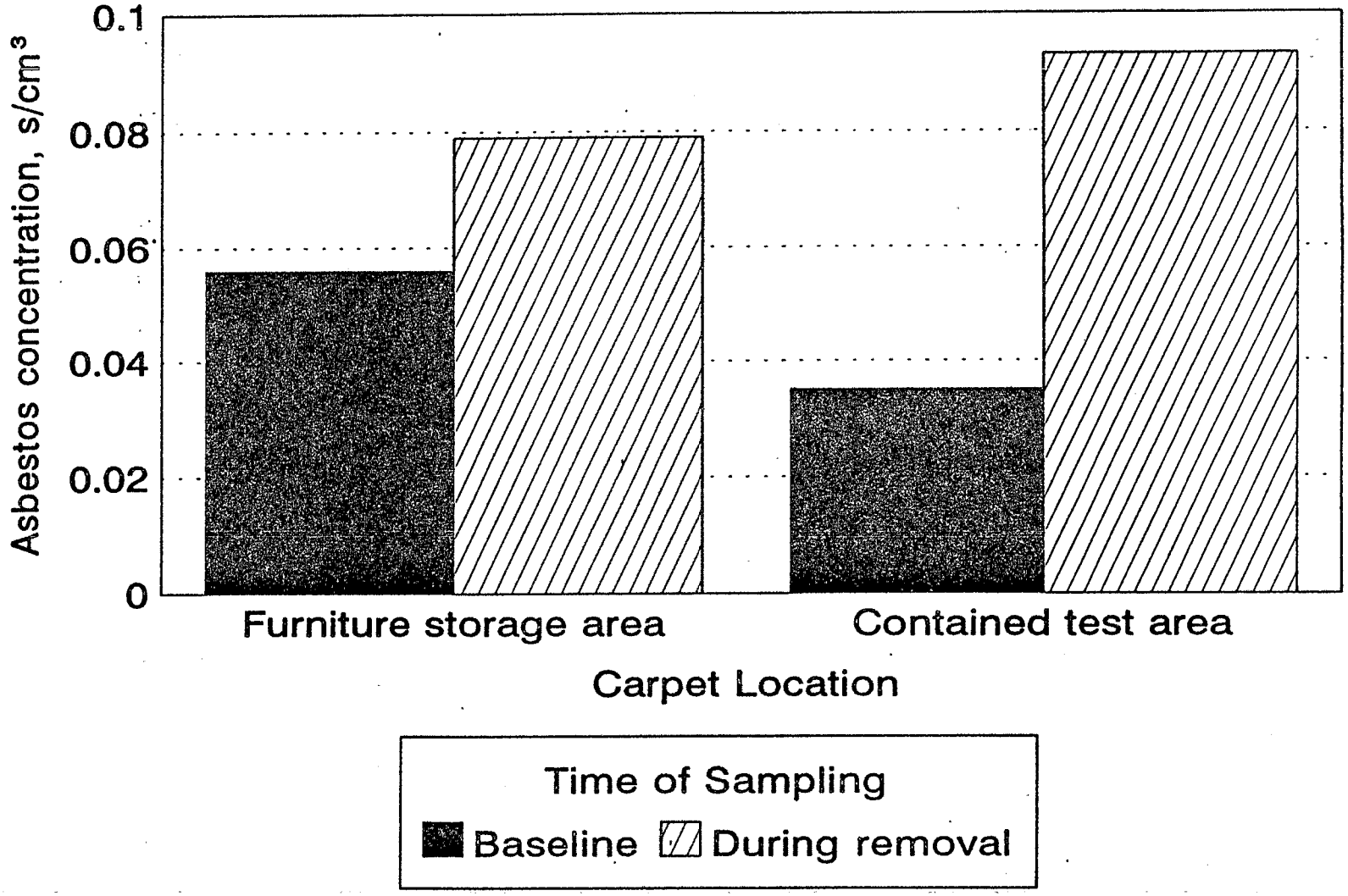


Figure 5. Area airborne asbestos concentrations (arithmetic mean) during carpet removal.

During the carpet-removal activities in the contained test area, a significant increase occurred in the average airborne asbestos concentration ($p=0.0004$). Specifically, a 95 percent confidence interval for the mean airborne asbestos concentration during carpet-removal activities as a proportion of the baseline concentration before removal showed that the mean airborne asbestos concentration was between 1.7 and 4.3 times greater during removal activities.

Effectiveness of Cleaning Methods

Figure 6 illustrates the average (geometric mean) concentrations of asbestos structures in the carpet before and after cleaning. The 95 percent confidence intervals for the geometric mean concentrations are presented in Table 11. Individual results for the carpet samples collected before and after cleaning are presented in Appendix H. For each experiment, a single estimated concentration was obtained before cleaning, after the first cleaning, and after the second cleaning by taking the arithmetic average of the three individual estimates. This yielded nine triplicates of concentrations, one for each experiment. The average asbestos concentrations in the carpet before and after cleaning are presented in Appendix I.

After 1st Cleaning

Results of the one-factor analysis of variance are summarized in Table 12. The type of cleaning method had a statistically significant effect on the difference between asbestos concentrations in the carpet before and after the first cleaning ($p=0.0164$); that is, the mean relative change in asbestos concentration in the carpet after cleaning varied significantly with the type of cleaner. The estimated asbestos concentration in the carpet after cleaning as a proportion of the asbestos concentration before cleaning for each cleaning method and the corresponding 95 percent confidence interval are presented in Table 13.

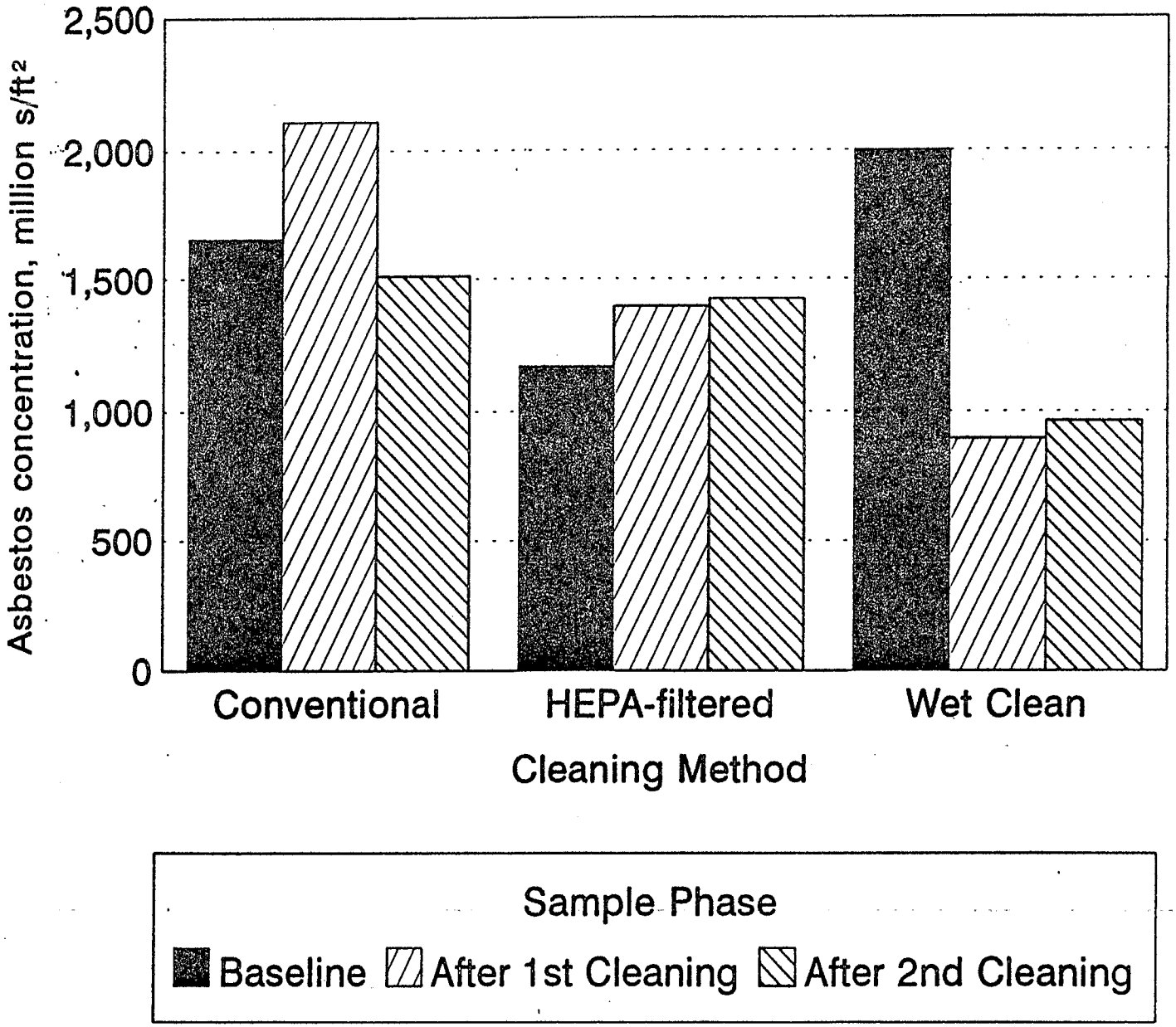


Figure 6. Asbestos concentrations (geometric mean) in the carpet before and after cleaning.

TABLE 11. SUMMARY STATISTICS FOR ASBESTOS CONCENTRATIONS IN CARPET BEFORE AND AFTER CLEANING

Cleaning method	Number of data points[a]	Asbestos concentration, billion s/ft^2 Geometric mean	95% CI[b]
	Baseline		
Conventional dry vacuum	3	1.6	(0.85, 3.1)
HEPA-filtered dry vacuum	3	1.1	(0.28, 4.0)
Hot-water extraction	3	2.0	(1.1, 3.5)
	After 1st cleaning		
Conventional dry vacuum	3	2.1	(1.2, 3.7)
HEPA-filtered dry vacuum	3	1.3	(0.39, 4.3)
Hot-water extraction	3	0.85	(0.32, 2.3)
	After 2nd cleaning		
Conventional dry vacuum	3	1.3	(0.23, 7.3)
HEPA-filtered dry vacuum	3	1.4	(0.82, 2.4)
Hot-water extraction	3	0.88	(0.24, 3.3)

[a]Each data point represents the average of three work-area samples.
[b]95 percent confidence interval for the geometric mean.

TABLE 12. ANALYSIS OF VARIANCE TABLE FOR DIFFERENCE BETWEEN ASBESTOS CONCENTRATIONS IN CARPET BEFORE AND AFTER CLEANING

Source of variation	Degrees of freedom	Sum of squares	F-value	p-value
Cleaning method	2	2.2432	8.80	0.0164
Error	6	0.7643		

TABLE 13. ESTIMATED ASBESTOS CONCENTRATION IN CARPET AFTER CLEANING AS A PROPORTION OF THE CONCENTRATION BEFORE CLEANING

Cleaning method	P*	95 percent confidence interval
Conventional dry vacuum	1.3	(0.75, 2.1)
HEPA-filtered dry vacuum	1.2	(0.74, 2.0)
Hot water extraction cleaner	0.43	(0.26, 0.72)

*Asbestos concentration in the carpet after cleaning as a proportion of the concentration before cleaning.

The asbestos concentration after wet cleaning was approximately 0.4 of the asbestos concentration before cleaning (i.e., a 60% reduction in the concentration). The upper 95 percent confidence limit for this proportion (Table 13) is less than 1, which indicates this is a statistically significant reduction.

The asbestos concentration in the carpet after dry vacuuming with a conventional and a HEPA-filtered dry vacuum cleaner was 1.3 and 1.2 times the concentration before cleaning, respectively (Table 13). The 95 percent confidence intervals for both estimates include the number 1, which indicates the data do not provide statistically significant evidence of either an increase or a decrease in asbestos concentration after dry vacuuming with either a conventional or a HEPA-filtered vacuum cleaner.

These results are consistent with the findings from the 1988 EPA controlled research study, which evaluated the efficacy of HEPA-filtered dry vacuum and HEPA-filtered hot-water extraction cleaners on carpet that was artificially contaminated with asbestos.[1,2] The controlled study similarly showed that the efficacy of wet cleaning was significantly greater than that of dry vacuuming. The study showed an approximately 70 percent reduction in

carpet contamination levels after wet cleaning, compared with an approximately 60 percent reduction in this study. The 1988 study likewise did not show statistically significant evidence of either an increase or a decrease in asbestos concentration after dry vacuuming.

After 2nd Cleaning

The carpet was dry-vacuumed or wet cleaned a second time to determine the effect of repeat vacuuming or cleaning. The type of cleaning method had no statistically significant effect on the difference between asbestos concentrations in the carpet after the first and second cleanings ($p=0.5314$). Results from the one-factor analysis of variance are summarized in Table 14. The estimated asbestos concentration in the carpet after the second cleaning as a proportion of the asbestos concentration after the first cleaning is given in Table 15 for each cleaning method, together with a 95 percent confidence. The 95 percent confidence intervals for these estimates include the number 1, which indicates the data do not provide statistically significant evidence of either an increase or a decrease in asbestos concentration after cleaning the carpet a second time.

TABLE 14. ANALYSIS OF VARIANCE TABLE FOR DIFFERENCE BETWEEN ASBESTOS CONCENTRATIONS AFTER THE FIRST AND SECOND CLEANINGS

Source of variation	Degrees of freedom	Sum of squares	F-value	p-value
Cleaning method	2	0.5522	0.70	0.5314
Error	6	0.2761		

TABLE 15. ESTIMATED ASBESTOS CONCENTRATION IN CARPET AFTER CLEANING AS A PROPORTION OF THE CONCENTRATION BEFORE CLEANING

Cleaning method	P[a]	95 percent confidence interval
Conventional dry vacuum	0.63	(0.26, 1.5)
HEPA-filtered dry vacuum	1.1	(0.45, 2.6)
Hot water extraction cleaner	1.0	(0.43, 2.5)

[a]Asbestos concentration in the carpet after the second cleaning as a proportion of the concentration after the first cleaning.

Comparison With 1988 Controlled Carpet Study

A controlled carpet-cleaning study was performed in 1988 with new carpet that had been sprayed with an aerosol containing known concentrations of chrysotile asbestos suspended in water.[1,2] After the carpet had dried, it was rolled with a 200-pound steel roller to simulate the effects of normal foot traffic in working the asbestos into the carpet. The results of the present study, which represent a real-world carpet with unknown contaminants, similar asbestos contamination levels (1.6 billion s/ft^2 average), and wear characteristics, are quite comparable with the results of the high concentration (1 billion s/ft^2) controlled experiment in terms of the reentrainment of asbestos during cleaning procedures; i.e., the airborne asbestos concentrations measured in the present study were 1.3 to 2 times greater during carpet cleaning versus 2 to 4 times greater as measured in the 1988 study. The results of the present study are also comparable regarding the effectiveness of the cleaning methods to remove asbestos structures from carpet; i.e., the present study showed a 60 percent reduction in asbestos concentrations in the carpet after wet-cleaning compared with a

70 percent reduction in the 1988 study. Both studies showed that dry vacuuming did not significantly change the asbestos concentration in the carpet.

Structure Morphology and Length Distributions

Carpet Samples

Table 16 presents the asbestos structure morphology and length distributions for the carpet samples collected before and after cleaning. Overall, the asbestos structures were primarily fibers and matrices, and to a lesser extent, bundles and clusters. Chrysotile and amosite represented approximately 96 and 4 percent, respectively, of the asbestos structures present in 18 baseline carpet samples. The distribution of chrysotile and amosite in the carpet was unaffected by cleaning; i.e., the data suggest that an equal percentage of chrysotile and amosite structures were removed or entrained into the air as a result of cleaning.

TABLE 16. ASBESTOS STRUCTURE DISTRIBUTIONS FROM CARPET SAMPLES COLLECTED BEFORE AND AFTER CLEANING

Sample	% Structures[a]					
	Chryso-tile	Amosite	Fibers	Bundles	Clusters	Matrices
	Dry vacuuming					
Baseline	96.3	3.7	55.8	9.8	2.4	31.9
After 1st cleaning	96.1	3.9	56.1	12.4	2.4	29.2
After 2nd cleaning	95.7	4.3	61.9	7.5	2.8	27.8
	Wet cleaning					
Baseline	96.5	3.5	68.0	7.3	1.5	23.2
After 1st cleaning	96.8	3.2	71.1	7.0	0.2	21.6
After 2nd cleaning	96.7	3.3	70.0	5.0	2.0	23.0

[a] Total percentage may exceed 100% because of rounding.

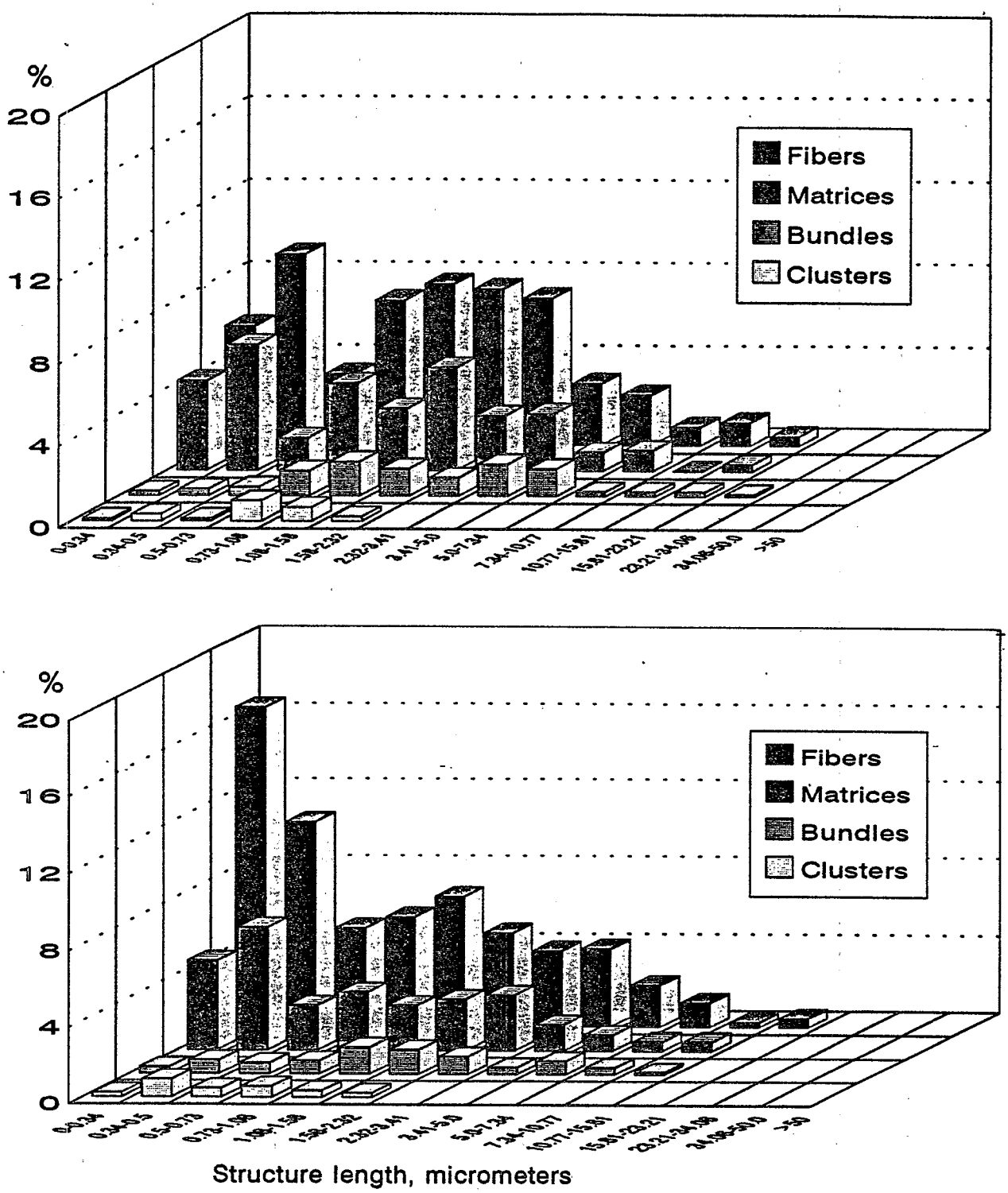


Figure 7. Asbestos particle distribution in carpet before (top) and after (bottom) dry vacuuming, as measured by TEM.

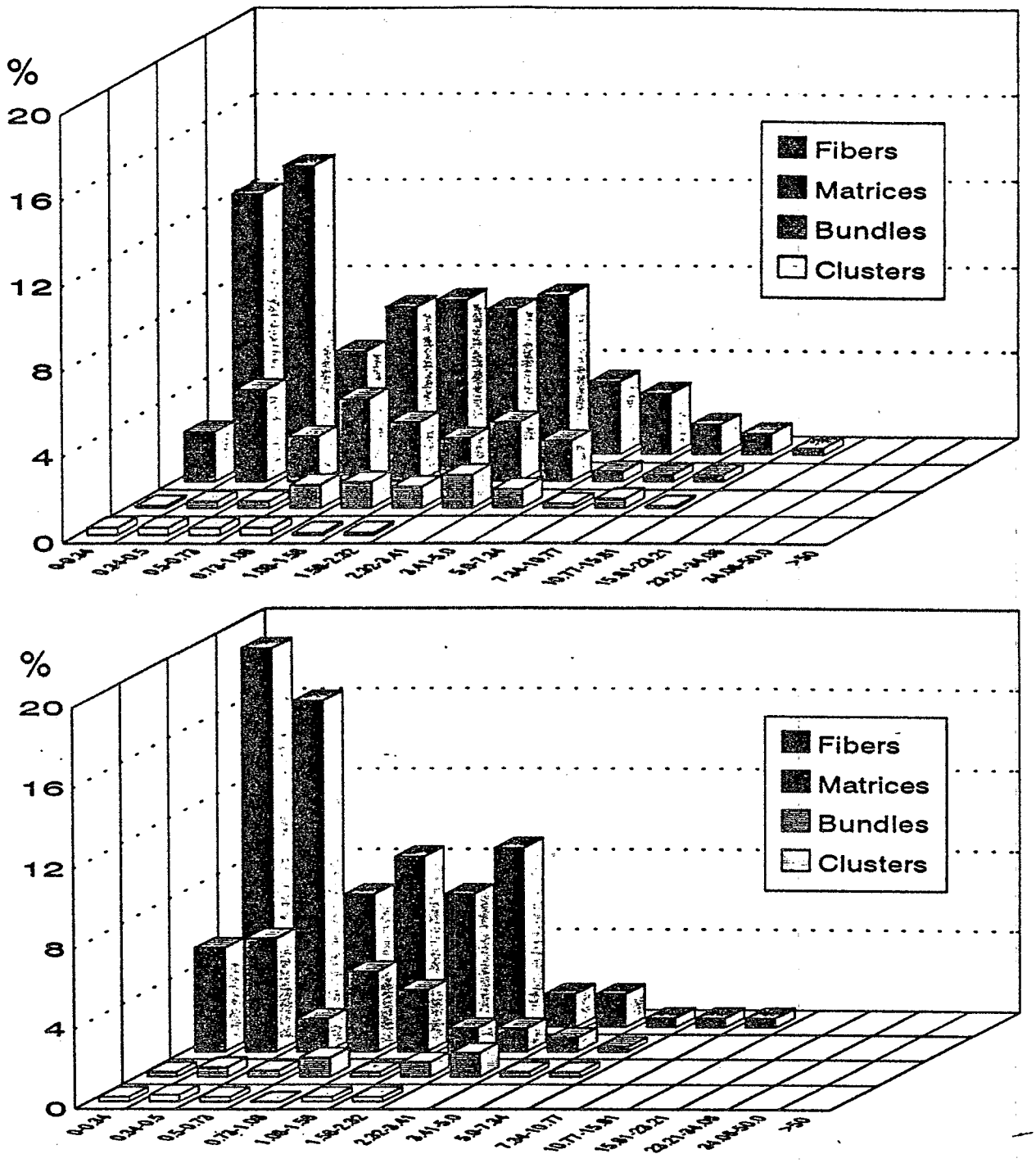


Figure 8. Asbestos particle size distribution in carpet before (top) and after (bottom) wet cleaning, as measured by TEM.

TABLE 17. ASBESTOS STRUCTURE DISTRIBUTIONS FROM AREA AIR SAMPLES COLLECTED BEFORE AND DURING CLEANING

Sample	% Structures[a]					
	Chryso-tile	Amosite	Fibers	Bundles	Clusters	Matrices
	Dry vacuuming					
Baseline	100	0	98	0.4	0	1.6
During cleaning	99.8	0.2	98	0.2	0.2	1.7
	Wet cleaning					
Baseline	97.6	2.4	96.3	0	1.2	2.4
During cleaning	98.2	1.8	75.4	2.9	0.6	21.1

[a] Total percentage may exceed 100% because of rounding.

The distribution of structure morphology was not greatly altered by dry vacuuming (Table 17). Wet cleaning, however, produced a substantially larger number of asbestos matrices than did dry vacuuming. Approximately 21 percent of the asbestos structures observed during wet cleaning were matrices compared with 1.7 percent and 2.4 percent for dry vacuuming and baseline measurements, respectively. There is no apparent reason why wet cleaning produced a substantially larger number of asbestos matrices than did dry vacuuming.

Figures 9 and 10 illustrate the size distributions of asbestos structures found in the air before and during cleaning. These same data are also presented by using a linear scale X-axis (Appendix J). Table 18 presents the cumulative size distributions of asbestos structures found in air both before and after carpet cleaning. The data presented in Figure 9 show a small decrease in the size and complexity of structures in the air during dry vacuuming, whereas Figure 10 shows a small increase in the size and complexity of structures during wet cleaning. Approximately 75 percent of the asbestos structures observed during wet cleaning were less

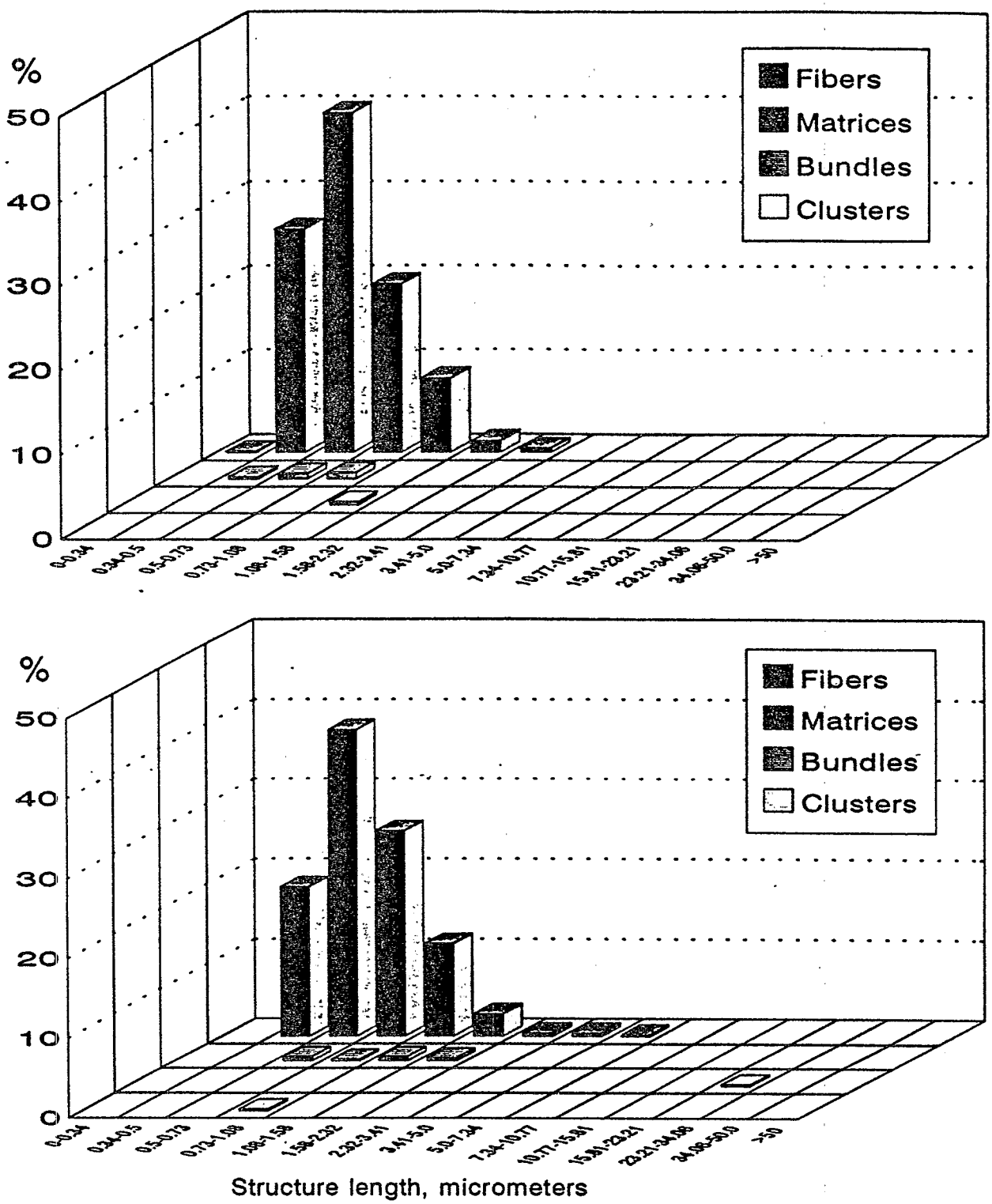


Figure 9. Asbestos particle size distribution in area air before (top) and during (bottom) dry vacuuming, as measured by TEM.

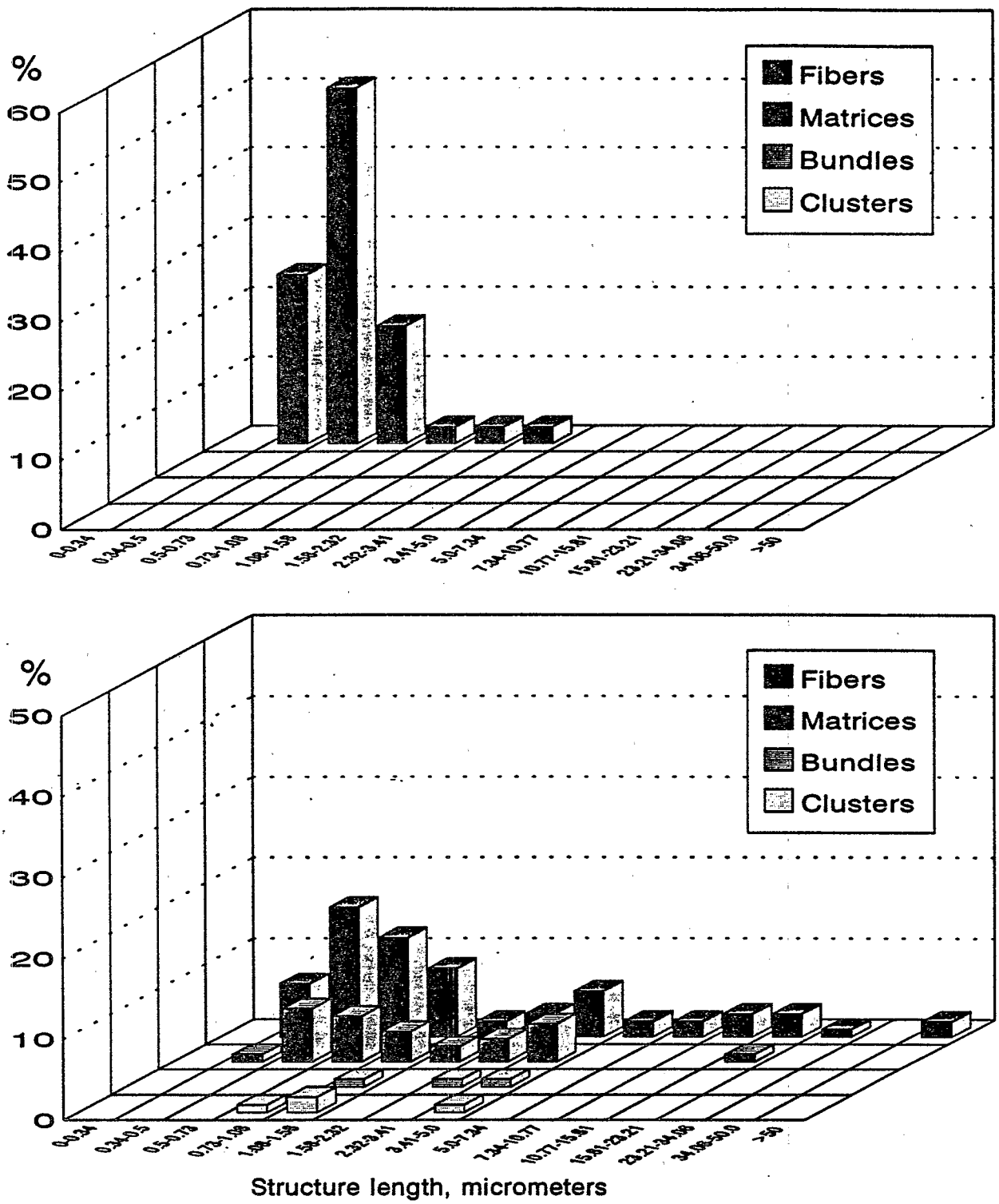


Figure 10. Asbestos particle size distribution in area air before (top) and during (bottom) wet cleaning, as measured by TEM.

than 2 μm in length compared with 97 percent for dry vacuuming (Table 18). Hence, the wet cleaning of carpet results in larger asbestos structures becoming airborne as opposed to dry vacuuming.

TABLE 18. CUMULATIVE SIZE DISTRIBUTIONS OF ASBESTOS STRUCTURES IN WORK-AREA AIR SAMPLES COLLECTED BEFORE AND DURING CARPET CLEANING

	% Structures and lengths, μm					
Sample	<1	<2	<3	<4	<5	<10
	Dry vacuuming					
Baseline	82.2	98.7	100	100	100	100
During cleaning	74.3	97.2	99.3	99.4	99.6	99.8
	Wet cleaning					
Baseline	72.0	95.1	97.6	98.8	98.8	98.8
During cleaning	50.9	74.9	87.1	93.0	97.1	98.8

Area Air Samples During Carpet Removal

Table 19 presents the asbestos structure morphology and length distributions for the area air samples collected during carpet removal (Experiments 10 and 11). As during carpet cleaning (Tables 16 and 17), chrysotile was the predominant form of asbestos found in the baseline air samples collected before cleaning. A larger proportion of amosite asbestos structures, however, were observed in samples collected during removal than in samples collected during cleaning or in baseline samples collected before removal. Approximately 11 and 26 percent of the asbestos structures observed in Experiments 10 and 11, respectively, were amosite, compared with less than 2 percent during cleaning with either method. The

distribution of structure morphology was similar to that for wet cleaning; i.e., the asbestos structures were primarily fibers and matrices, and to a lesser extent, bundles and clusters.

TABLE 19. ASBESTOS STRUCTURE DISTRIBUTIONS FROM AREA AIR SAMPLES COLLECTED DURING CARPET REMOVAL

Sample	% Structures[a]					
	Chryso-tile	Amosite	Fibers	Bundles	Clusters	Matrices
			Experiment 10			
Baseline	97.1	2.9	81.2	4.3	4.3	10.1
During removal	88.7	11.3	67.0	4.1	5.2	23.7
			Experiment 11			
Baseline	100	0	100	0	0	0
During removal	73.6	26.4	66	2.8	3.8	27.4

[a] Total percentages may exceed 100% because of rounding.

Figures 11 and 12 illustrate the size distributions of asbestos structures found in the air before and during carpet removal. These same data are also presented by using a linear X-axis scale (Appendix J). Comparison of the data presented in Figures 11 and 12 shows a notable decrease in size and increase in complexity of asbestos structures in the air during the removal of carpet compared with baseline measurements. During Experiment 11 (removal of the carpet that had been cleaned in Experiments 1 through 9), approximately 37 percent of the observed asbestos structures were less than 1 μm in length compared with approximately 83 percent for the baseline measurements (Table 20). None of the baseline measurements for

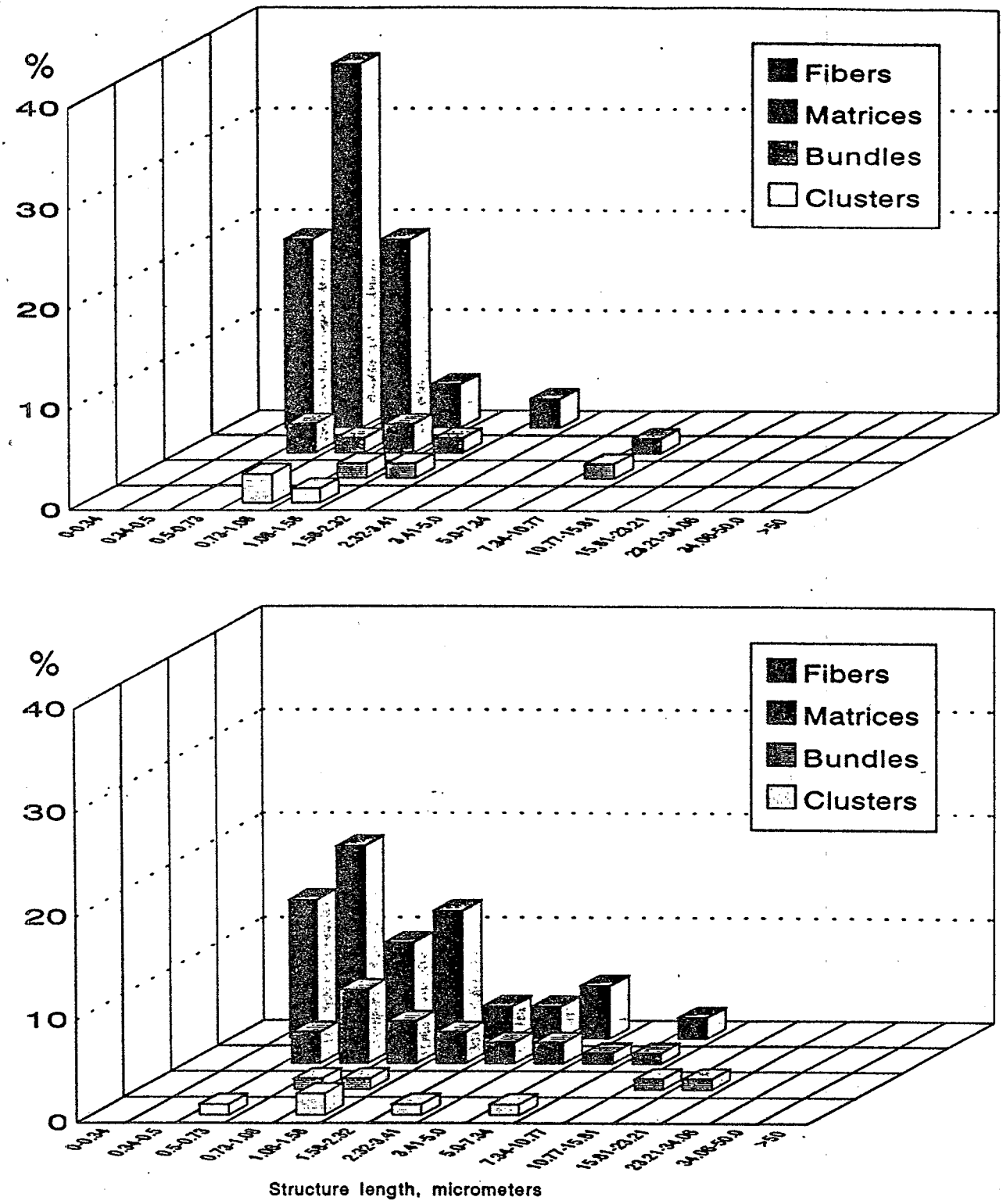


Figure 11. Particle size distribution in area air samples before (Top) and during (bottom) removal of cleaned carpet.

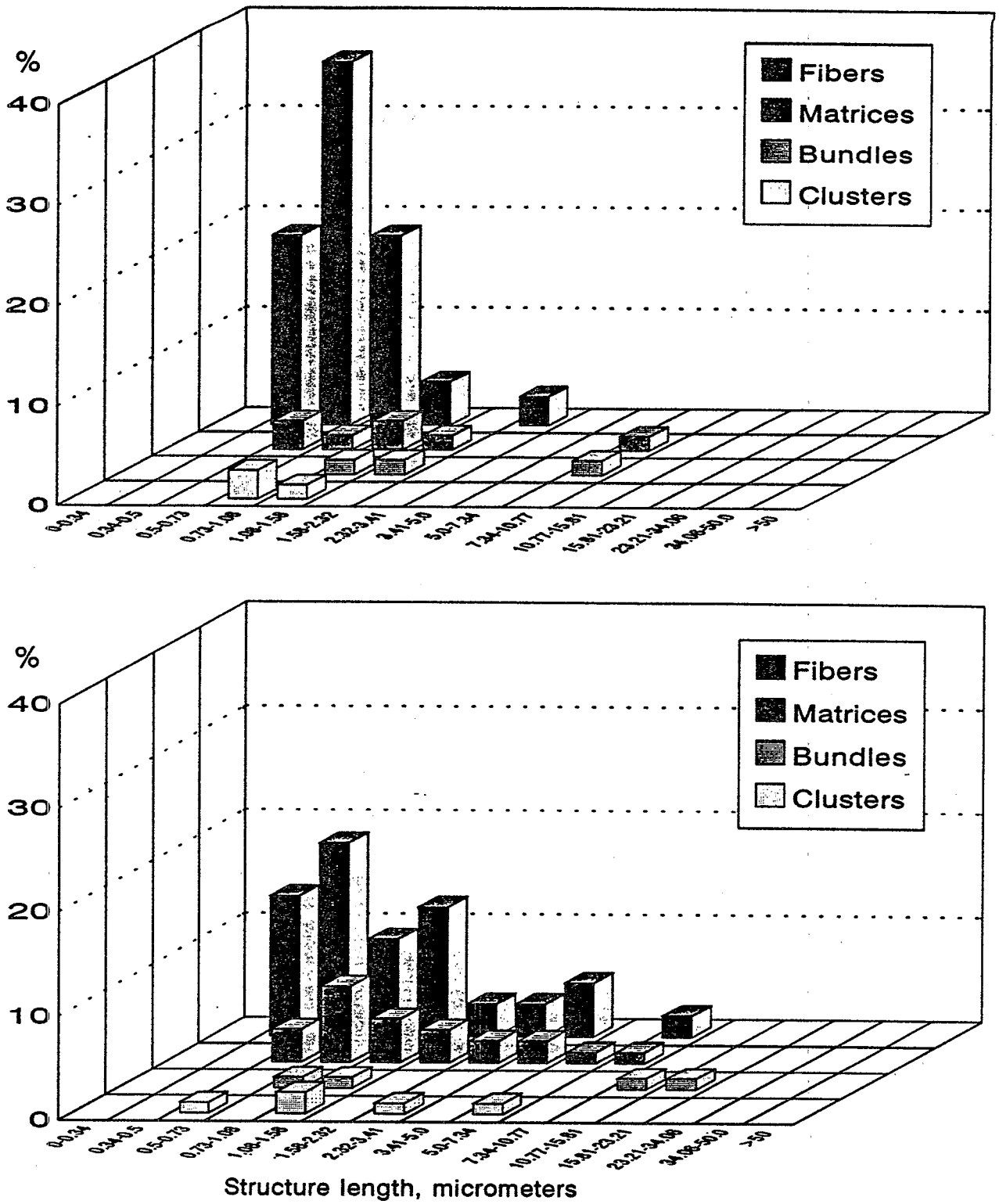


Figure 12. Asbestos particle size distribution in area air samples before (top) and during (bottom) removal of cleaned carpet.

Experiment 11 showed structures greater than 10 μm in length, whereas 10 percent of the structures observed during carpet removal were greater than 10 μm in length. Hence, carpet-removal activities are more likely to release large asbestos structures into the air.

TABLE 20. CUMULATIVE SIZE DISTRIBUTIONS OF ASBESTOS STRUCTURES IN WORK AREA AIR SAMPLES COLLECTED BEFORE AND DURING CARPET REMOVAL

	% Structures and lengths, μm					
Sample	<1	<2	<3	<4	<5	<10
	Experiment 10					
Baseline	71	92.8	97.1	97.1	97.1	100
During cleaning	45.4	75.3	82.5	86.6	89.7	95.9
	Experiment 11					
Baseline	82.9	95.1	97.6	97.6	100	100
During cleaning	36.8	64.2	73.6	79.2	84.0	90.6

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APPENDIX A

SONICATION PROCEDURE FOR EXTRACTION OF ASBESTOS STRUCTURES FROM CARPET SAMPLES

Analytical Method:

A sonication procedure will be used to extract asbestos particles from the carpet swatch samples for subsequent analysis by TEM.

Sample preparation: A 5-cm x 5-cm area of carpet is placed carpet-side down into a 1000-mL polypropylene disposable beaker containing 100 mL of a 0.1 percent solution (by volume) of Aerosol OT made with distilled water. The beaker and its contents are placed in an ultrasonic bath and sonicated three times, 10 minutes each time. After each sonication, the solution is drained into a 500-mL polyethylene screw-cap container and another 100 mL of fresh Aerosol OT solution is added for the next sonication. The carpet is then removed from the beaker and the beaker is rinsed with 100 mL of distilled water.

The rinse from the beaker is added to the sample container. The resultant suspension is shaken vigorously to achieve a "homogeneous suspension of fibers" and then allowed to sit for 2 minutes. Aliquots of 1-, 5-, 25-, and 125-ml volume are extracted with a disposable graduated pipette. (These four measured aliquots of different volumes should be sufficient to attain an acceptable fiber loading.) Each aliquot is then poured through an approximately 100-mesh stainless steel screen into the top of a filtration apparatus (Millipore Corporation Cat. No. XX10 025 00). A new glass funnel is used for each carpet sample as well as for each laboratory blank. (The purpose of the coarse-mesh screen is to remove large nonasbestos structures from the sample solution before filtration.) The filtration apparatus contains a 0.22-μm pore size, 25-mm-diameter mixed cellulose ester (MCE) filter (having an effective area of 230 mm^2) backed by a 0.8- to 5-μm pore size, 25-mm MCE filter.

When filtration is complete, the 0.22-μm mixed cellulose ester filter is carefully removed from the funnel assembly and placed in a Gelman "Analyslide" dish or equivalent. The filter is dried before proceeding with the preparation procedure.

Filter Preparation and TEM Analysis: Portions of the 0.22-μm MCE filter are prepared and analyzed in accordance with the nonmandatory TEM method as described in the Asbestos Hazard Emergency Response Act (AHERA) final rule (40 CFR 763). Counting is performed on a sufficient number of grid openings to achieve the required analytical sensitivity of 1 million asbestos structures per square foot, or completion of the grid opening on which the 100th asbestos fiber was observed. The fiber-counting results will be expressed in terms of asbestos structures per square foot of original carpet.

Duplicate Analysis

A duplicate analysis is the analysis of a second TEM grid prepared from a different area of the sample filter and analyzed by the same microscopist as the original analysis.

Sample Blank

A sample blank is a sample prepared in a manner identical to that used for the carpet swatch samples, but no carpet sample is used. These blanks serve as a Quality Control check on contamination from solutions, glassware, filters, and handling procedures. One sample blank will be prepared for every 15 samples analyzed.

APPENDIX B
Individual Airborne Asbestos Concentrations
Before and During Carpet Cleaning, as Determined Using TEM
(Page 1 of 2)

Experiment	Cleaning Method	Sample Type	Sample Number	Concentration, s/cm^3
01	CONVENTIONAL DRY VACUUM	DURING CLEANING	01A-01D	0.671
01	CONVENTIONAL DRY VACUUM	DURING CLEANING	01A-02D	0.885
01	CONVENTIONAL DRY VACUUM	DURING CLEANING	01A-06D	0.685
01	CONVENTIONAL DRY VACUUM	BASELINE	01A-01B	0.656
01	CONVENTIONAL DRY VACUUM	BASELINE	01A-02B	1.852
01	CONVENTIONAL DRY VACUUM	BASELINE	01A-05B	0.864
01	CONVENTIONAL DRY VACUUM	DURING CLEANING	01P-01D	0.640
02	HEPA-FILTERED DRY VACUUM	DURING CLEANING	02A-01D	0.146
02	HEPA-FILTERED DRY VACUUM	DURING CLEANING	02A-03D	0.207
02	HEPA-FILTERED DRY VACUUM	DURING CLEANING	02A-05D	0.152
02	HEPA-FILTERED DRY VACUUM	BASELINE	02A-02B	0.274
02	HEPA-FILTERED DRY VACUUM	BASELINE	02A-03B	0.093
02	HEPA-FILTERED DRY VACUUM	BASELINE	02A-06B	0.121
02	HEPA-FILTERED DRY VACUUM	DURING CLEANING	02P-01D	0.124
03	HOT-WATER EXTRACTION	DURING CLEANING	03A-01D	0.146
03	HOT-WATER EXTRACTION	DURING CLEANING	03A-05D	0.060
03	HOT-WATER EXTRACTION	DURING CLEANING	03A-06D	0.120
03	HOT-WATER EXTRACTION	BASELINE	03A-01B	0.088
03	HOT-WATER EXTRACTION	BASELINE	03A-03B	0.044
03	HOT-WATER EXTRACTION	BASELINE	03A-06B	0.035
03	HOT-WATER EXTRACTION	DURING CLEANING	03P-03D	0.117
04	HOT-WATER EXTRACTION	DURING CLEANING	04A-02D	0.089
04	HOT-WATER EXTRACTION	DURING CLEANING	04A-03D	0.072
04	HOT-WATER EXTRACTION	DURING CLEANING	04A-04D	0.152
04	HOT-WATER EXTRACTION	BASELINE	04A-02B	0.025
04	HOT-WATER EXTRACTION	BASELINE	04A-05B	0.049
04	HOT-WATER EXTRACTION	BASELINE	04A-06B	0.045
04	HOT-WATER EXTRACTION	DURING CLEANING	04P-03D	0.093
05	CONVENTIONAL DRY VACUUM	DURING CLEANING	05A-02D	0.054
05	CONVENTIONAL DRY VACUUM	DURING CLEANING	05A-04D	0.067
05	CONVENTIONAL DRY VACUUM	DURING CLEANING	05A-06D	0.073
05	CONVENTIONAL DRY VACUUM	BASELINE	05A-03B	0.039
05	CONVENTIONAL DRY VACUUM	BASELINE	05A-05B	0.064
05	CONVENTIONAL DRY VACUUM	BASELINE	05A-06B	0.056
05	CONVENTIONAL DRY VACUUM	DURING CLEANING	05P-03D	0.025
06	HEPA-FILTERED DRY VACUUM	DURING CLEANING	06A-01D	0.095
06	HEPA-FILTERED DRY VACUUM	DURING CLEANING	06A-02D	0.062
06	HEPA-FILTERED DRY VACUUM	DURING CLEANING	06A-05D	0.055
06	HEPA-FILTERED DRY VACUUM	BASELINE	06A-02B	0.034
06	HEPA-FILTERED DRY VACUUM	BASELINE	06A-03B	0.045
06	HEPA-FILTERED DRY VACUUM	BASELINE	06A-05B	0.068
07	HEPA-FILTERED DRY VACUUM	DURING CLEANING	07A-02D	0.054
07	HEPA-FILTERED DRY VACUUM	DURING CLEANING	07A-03D	0.031
07	HEPA-FILTERED DRY VACUUM	DURING CLEANING	07A-05D	0.044
07	HEPA-FILTERED DRY VACUUM	BASELINE	07A-01B	0.025

Experiment	Cleaning Method	Sample Type	Sample Number	Concentration, s/cm^3
07	HEPA-FILTERED DRY VACUUM	BASELINE	07A-03B	0.035
07	HEPA-FILTERED DRY VACUUM	BASELINE	07A-05B	0.014
08	HOT-WATER EXTRACTION	DURING CLEANING	08A-01D	0.056
08	HOT-WATER EXTRACTION	DURING CLEANING	08A-03D	0.089
08	HOT-WATER EXTRACTION	DURING CLEANING	08A-04D	0.054
08	HOT-WATER EXTRACTION	BASELINE	08A-02B	0.044
08	HOT-WATER EXTRACTION	BASELINE	08A-05B	0.056
08	HOT-WATER EXTRACTION	BASELINE	08A-06B	0.026
08	HOT-WATER EXTRACTION	DURING CLEANING	08P-03D	0.034
09	CONVENTIONAL DRY VACUUM	DURING CLEANING	09A-01D	0.042
09	CONVENTIONAL DRY VACUUM	DURING CLEANING	09A-04D	0.047
09	CONVENTIONAL DRY VACUUM	DURING CLEANING	09A-06D	0.000
09	CONVENTIONAL DRY VACUUM	BASELINE	09A-02B	0.025
09	CONVENTIONAL DRY VACUUM	BASELINE	09A-04B	0.015
09	CONVENTIONAL DRY VACUUM	BASELINE	09A-05B	0.005

Appendix C
Average Airborne Asbestos Concentrations (Determined by TEM) Before and During Carpet Cleaning

Cleaning Method	Experiment	Average Concentration, s/cm^3	
		Baseline	During cleaning
CONVENTIONAL DRY VACUUM	1	1.12	0.747
	5	0.053	0.065
	7	0.015	0.030
HEPA-FILTERED DRY VACUUM	2	0.163	0.168
	6	0.049	0.071
	7	0.025	0.043
HOT WATER EXTRACTION	3	0.056	0.109
	4	0.040	0.071
	8	0.042	0.066

Appendix D
Individual Personal Breathing Zone
Concentrations (Determined by PCM) During Carpet Cleaning

Experiment	Cleaning Method	Sample Number	Concentration, f/cm^3
01	CONVENTIONAL DRY VACUUM	01P-01D	0.016
01	CONVENTIONAL DRY VACUUM	01P-01RD	0.001
01	CONVENTIONAL DRY VACUUM	01P-02D	0.015
01	CONVENTIONAL DRY VACUUM	01P-02RD	0.006
01	CONVENTIONAL DRY VACUUM	01P-03D	0.007
01	CONVENTIONAL DRY VACUUM	01P-03RD	0.019
02	HEPA-FILTERED DRY VACUUM	02P-01D	0.017
02	HEPA-FILTERED DRY VACUUM	02P-01RD	0.000
02	HEPA-FILTERED DRY VACUUM	02P-02D	0.011
02	HEPA-FILTERED DRY VACUUM	02P-02RD	0.004
02	HEPA-FILTERED DRY VACUUM	02P-03D	0.008
02	HEPA-FILTERED DRY VACUUM	02P-03RD	0.013
03	HOT-WATER EXTRACTION	03P-01D	0.014
03	HOT-WATER EXTRACTION	03P-01RD	0.020
03	HOT-WATER EXTRACTION	03P-02D	0.018
03	HOT-WATER EXTRACTION	03P-02RD	0.020
03	HOT-WATER EXTRACTION	03P-03D	0.021
03	HOT-WATER EXTRACTION	03P-03RD	0.016
04	HOT-WATER EXTRACTION	04P-01D	0.008
04	HOT-WATER EXTRACTION	04P-01RD	0.020
04	HOT-WATER EXTRACTION	04P-02D	0.007
04	HOT-WATER EXTRACTION	04P-02RD	0.010
04	HOT-WATER EXTRACTION	04P-03D	0.012
04	HOT-WATER EXTRACTION	04P-03RD	0.014
05	CONVENTIONAL DRY VACUUM	05P-01D	0.011
05	CONVENTIONAL DRY VACUUM	05P-01RD	0.000
05	CONVENTIONAL DRY VACUUM	05P-02D	0.003
05	CONVENTIONAL DRY VACUUM	05P-02RD	0.000
05	CONVENTIONAL DRY VACUUM	05P-03D	0.000
05	CONVENTIONAL DRY VACUUM	05P-03RD	0.000
06	HEPA-FILTERED DRY VACUUM	06P-01D	0.020
06	HEPA-FILTERED DRY VACUUM	06P-01RD	0.015
06	HEPA-FILTERED DRY VACUUM	06P-02D	0.021
06	HEPA-FILTERED DRY VACUUM	06P-02RD	0.024
06	HEPA-FILTERED DRY VACUUM	06P-03D	0.012
06	HEPA-FILTERED DRY VACUUM	06P-03RD	0.015
07	HEPA-FILTERED DRY VACUUM	07P-01D	0.011
07	HEPA-FILTERED DRY VACUUM	07P-01RD	0.014
07	HEPA-FILTERED DRY VACUUM	07P-02D	0.006
07	HEPA-FILTERED DRY VACUUM	07P-02RD	0.016
07	HEPA-FILTERED DRY VACUUM	07P-03D	0.006
07	HEPA-FILTERED DRY VACUUM	07P-03RD	0.010
08	HOT-WATER EXTRACTION	08P-01D	0.015
08	HOT-WATER EXTRACTION	08P-01RD	0.016
08	HOT-WATER EXTRACTION	08P-02D	0.015

Appendix D
(Page 2 of 2)

Experiment	Cleaning Method	Sample Number	Concentration, f/cm^3
08	HOT-WATER EXTRACTION	08P-02RD	0.022
08	HOT-WATER EXTRACTION	08P-03D	0.005
08	HOT-WATER EXTRACTION	08P-03RD	0.006
09	CONVENTIONAL DRY VACUUM	09P-01D	0.033
09	CONVENTIONAL DRY VACUUM	09P-01RD	0.019
09	CONVENTIONAL DRY VACUUM	09P-02D	0.012
09	CONVENTIONAL DRY VACUUM	09P-02RD	0.024
09	CONVENTIONAL DRY VACUUM	09P-03D	0.018
09	CONVENTIONAL DRY VACUUM	09P-03RD	0.023

Appendix E
Average Personal Breathing Zone Concentrations
(Determined by PCM) During Carpet Cleaning

Cleaning Method	Experiment	Average Concentration, f/cm^3	
		During 1st cleaning	During 2nd cleaning
CONVENTIONAL DRY VACUUM	1	0.013	0.009
	5	0.005	0
	7	0.021	0.022
HEPA-FILTERED DRY VACUUM	2	0.012	0.006
	6	0.018	0.018
	7	0.008	0.013
HOT WATER EXTRACTION	3	0.018	0.019
	4	0.009	0.015
	8	0.012	0.015

Appendix F
Individual Airborne Asbestos Concentrations
(Determined by TEM) During Carpet Removal

Experiment	Cleaning Method	Sample Type	Sample Number	Concentration, s/cm^3
10	CARPET REMOVAL	DURING CLEANING	10A-01D	0.051
10	CARPET REMOVAL	DURING CLEANING	10A-02D	0.106
10	CARPET REMOVAL	DURING CLEANING	10A-03D	0.052
10	CARPET REMOVAL	DURING CLEANING	10A-04D	0.103
10	CARPET REMOVAL	DURING CLEANING	10A-05D	0.097
10	CARPET REMOVAL	DURING CLEANING	10A-06D	0.064
10	CARPET REMOVAL	BASELINE	10A-01B	0.030
10	CARPET REMOVAL	BASELINE	10A-02B	0.061
10	CARPET REMOVAL	BASELINE	10A-03B	0.054
10	CARPET REMOVAL	BASELINE	10A-04B	0.066
10	CARPET REMOVAL	BASELINE	10A-05B	0.075
10	CARPET REMOVAL	BASELINE	10A-06B	0.052
11	CARPET REMOVAL	DURING CLEANING	11A-01D	0.082
11	CARPET REMOVAL	DURING CLEANING	11A-02D	0.073
11	CARPET REMOVAL	DURING CLEANING	11A-03D	0.082
11	CARPET REMOVAL	DURING CLEANING	11A-04D	0.075
11	CARPET REMOVAL	DURING CLEANING	11A-05D	0.155
11	CARPET REMOVAL	DURING CLEANING	11A-06D	0.090
11	CARPET REMOVAL	BASELINE	11A-01B	0.034
11	CARPET REMOVAL	BASELINE	11A-02B	0.036
11	CARPET REMOVAL	BASELINE	11A-03B	0.041
11	CARPET REMOVAL	BASELINE	11A-04B	0.015
11	CARPET REMOVAL	BASELINE	11A-05B	0.052
11	CARPET REMOVAL	BASELINE	11A-06B	0.034
11	CARPET REMOVAL	DURING CLEANING	11P-04D	0.050

Appendix G
Individual Personal Breathing Zone Concentrations
(Determined by PCM) During Carpet Removal

Experiment	Cleaning Method	Sample Number	Concentration, f/cm^3
10	CARPET REMOVAL	10P-01D	0.033
10	CARPET REMOVAL	10P-02D	0.059
11	CARPET REMOVAL	11P-01D	0.045
11	CARPET REMOVAL	11P-02D	0.090
11	CARPET REMOVAL	11P-03D	0.091
11	CARPET REMOVAL	11P-04D	0.061
11	CARPET REMOVAL	11P-05D	0.081
11	CARPET REMOVAL	11P-06D	0.047

Appendix H

Individual Asbestos Concentrations (Determined by TEM) in Carpet Before and After Cleaning

Experiment	Cleaning Method	Sample set	Concentration (s/ft^2) Baseline	After 1st cleaning	After 2nd cleaning
1	CONVENTIONAL DRY VACUUM	1	812,405,635	927,505,190	617,389,910
1	CONVENTIONAL DRY VACUUM	2	3,861,326,461	1,850,263,552	1,322,319,810
1	CONVENTIONAL DRY VACUUM	3	1,419,491,276	2,579,058,982	2,158,861,080
5	CONVENTIONAL DRY VACUUM	1	1,492,035,834	2,244,805,044	516,407,651
5	CONVENTIONAL DRY VACUUM	2	946,029,303	1,421,627,634	748,027,926
9	CONVENTIONAL DRY VACUUM	1	1,940,638,488	997,370,569	4,760,177,713
9	CONVENTIONAL DRY VACUUM	2	1,844,932,609	2,637,277,946	1,387,806,913
9	CONVENTIONAL DRY VACUUM	3	1,408,923,145	4,495,360,134	1,458,144,106
2	HEPA-FILTERED DRY VACUUM	1	1,248,055,132	893,235,062	1,285,771,083
2	HEPA-FILTERED DRY VACUUM	2	509,278,272	477,603,515	343,620,374
2	HEPA-FILTERED DRY VACUUM	3	642,143,751	990,401,477	1,884,527,691
6	HEPA-FILTERED DRY VACUUM	1	574,094,165	1,157,662,267	408,089,431
6	HEPA-FILTERED DRY VACUUM	2	130,840,065	947,022,535	529,265,042
6	HEPA-FILTERED DRY VACUUM	3	1,551,019,716	1,914,781,349	3,017,519,517
7	HEPA-FILTERED DRY VACUUM	1	1,807,734,155	1,184,377,550	1,560,888,936
7	HEPA-FILTERED DRY VACUUM	2	1,753,190,452	2,986,917,067	3,128,589,023
7	HEPA-FILTERED DRY VACUUM	3	2,329,716,606	2,012,922,371	657,014,173
3	HOT-WATER EXTRACTION	1	1,294,431,269	1,870,715,604	272,170,780
3	HOT-WATER EXTRACTION	2	1,614,200,034	282,869,638	532,203,020
3	HOT-WATER EXTRACTION	3	2,349,153,044	1,524,315,068	670,058,539
4	HOT-WATER EXTRACTION	1	1,668,878,386	113,226,980	1,417,691,804
4	HOT-WATER EXTRACTION	2	2,355,121,178	269,588,047	2,241,241,862
4	HOT-WATER EXTRACTION	3	1,073,813,668	1,308,400,654	441,665,524
8	HOT-WATER EXTRACTION	1	2,497,058,902	596,961,244	1,276,301,980
8	HOT-WATER EXTRACTION	2	1,659,398,371	1,780,668,002	963,369,299
8	HOT-WATER EXTRACTION	3	3,499,338,600	311,702,513	854,324,638

Appendix I
Average Asbestos Concentrations (Determined by TEM)
in the Carpet Before and After Cleaning

Cleaning Method	Experiment	Average Concentration (s/ft^2)		
		Baseline	After 1st cleaning	After 2nd cleaning
CONVENTIONAL DRY VACUUM	1	2,031,074,457	1,785,609,241	1,366,190,266
	5	1,219,032,568	1,833,216,339	632,217,788
	7	1,731,498,080	2,710,002,883	2,535,376,244
HEPA-FILTERED DRY VACUUM	2	799,825,718	787,080,018	1,171,306,382
	6	751,984,648	1,339,822,050	1,318,291,330
	7	1,963,547,071	2,061,405,662	1,782,164,044
HOT WATER EXTRACTION	3	1,752,594,782	1,225,966,770	491,477,446
	4	1,699,271,077	563,738,560	1,366,866,396
	8	2,551,931,957	896,443,919	1,031,331,972

APPENDIX J

SIZE DISTRIBUTIONS OF ASBESTOS STRUCTURES IN CARPET AND IN AIR PLOTTED BY USING A LINEAR X-AXIS SCALE

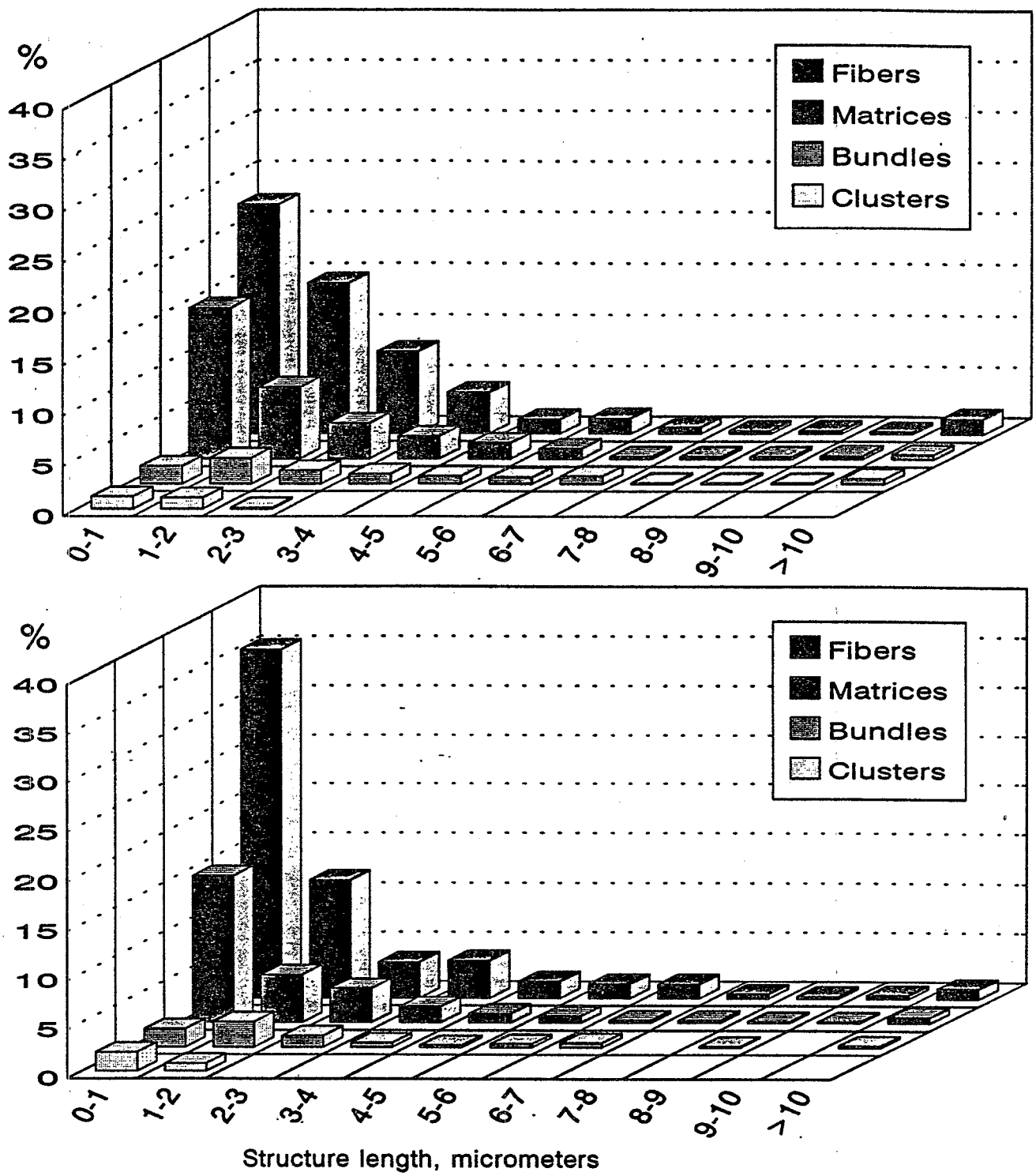

Figure J-1. Particle size distribution in carpet before (top) and after (bottom) dry vacuuming.

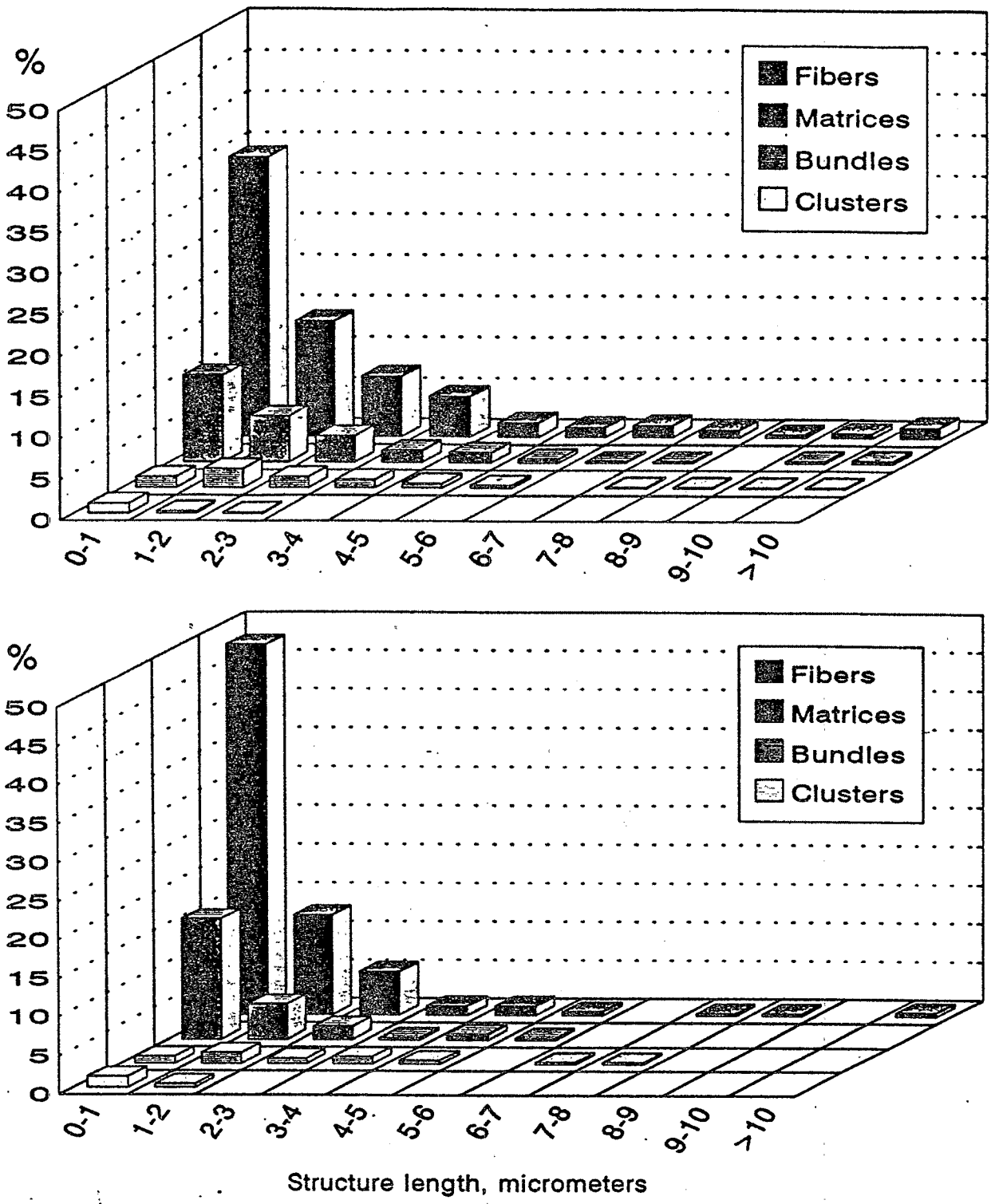

Figure J-2. Particle size distribution in carpet before (top) and after (bottom) wet cleaning.

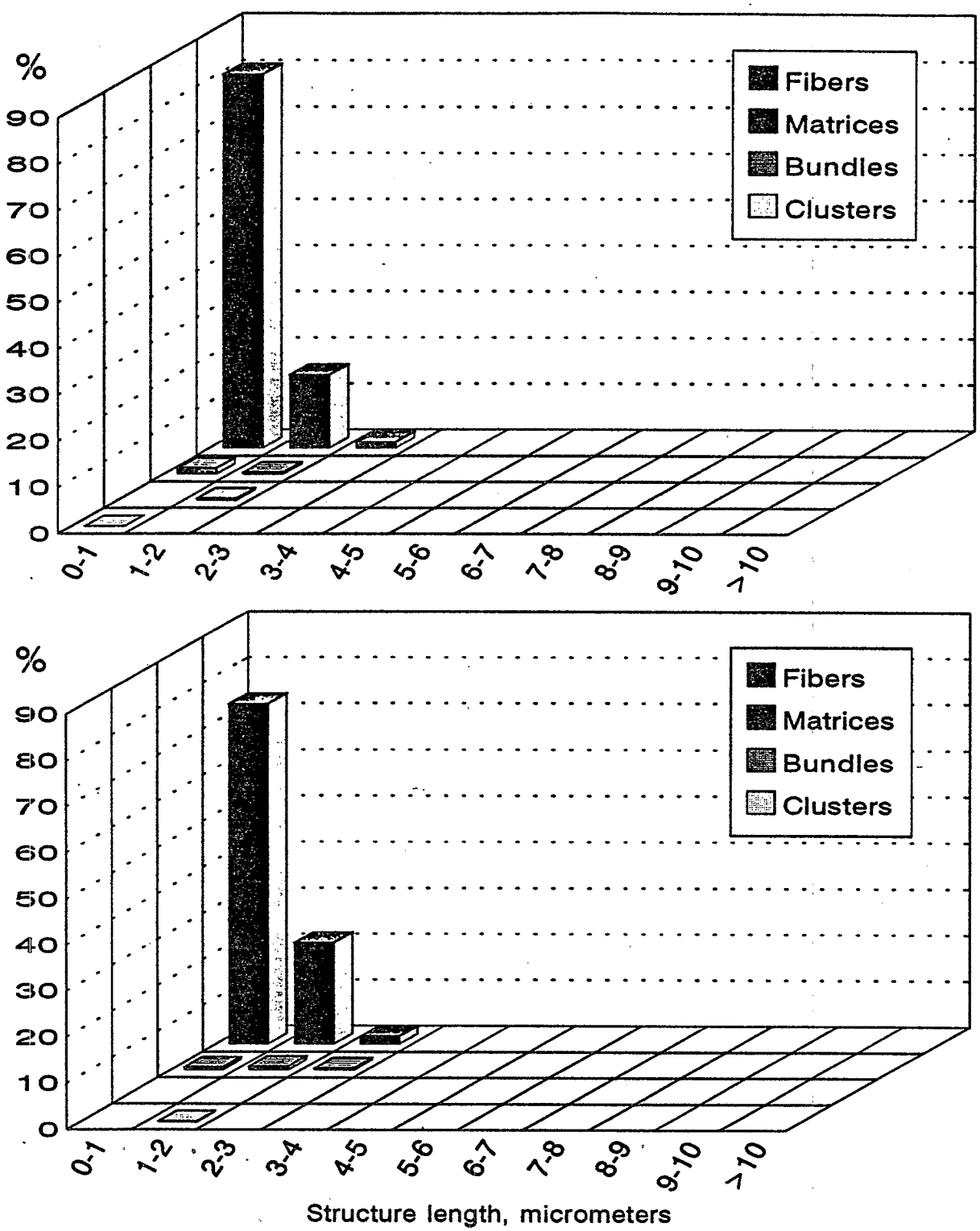

Figure J-3. Particle size distribution in area air before (top) and during (bottom) dry vacuuming.

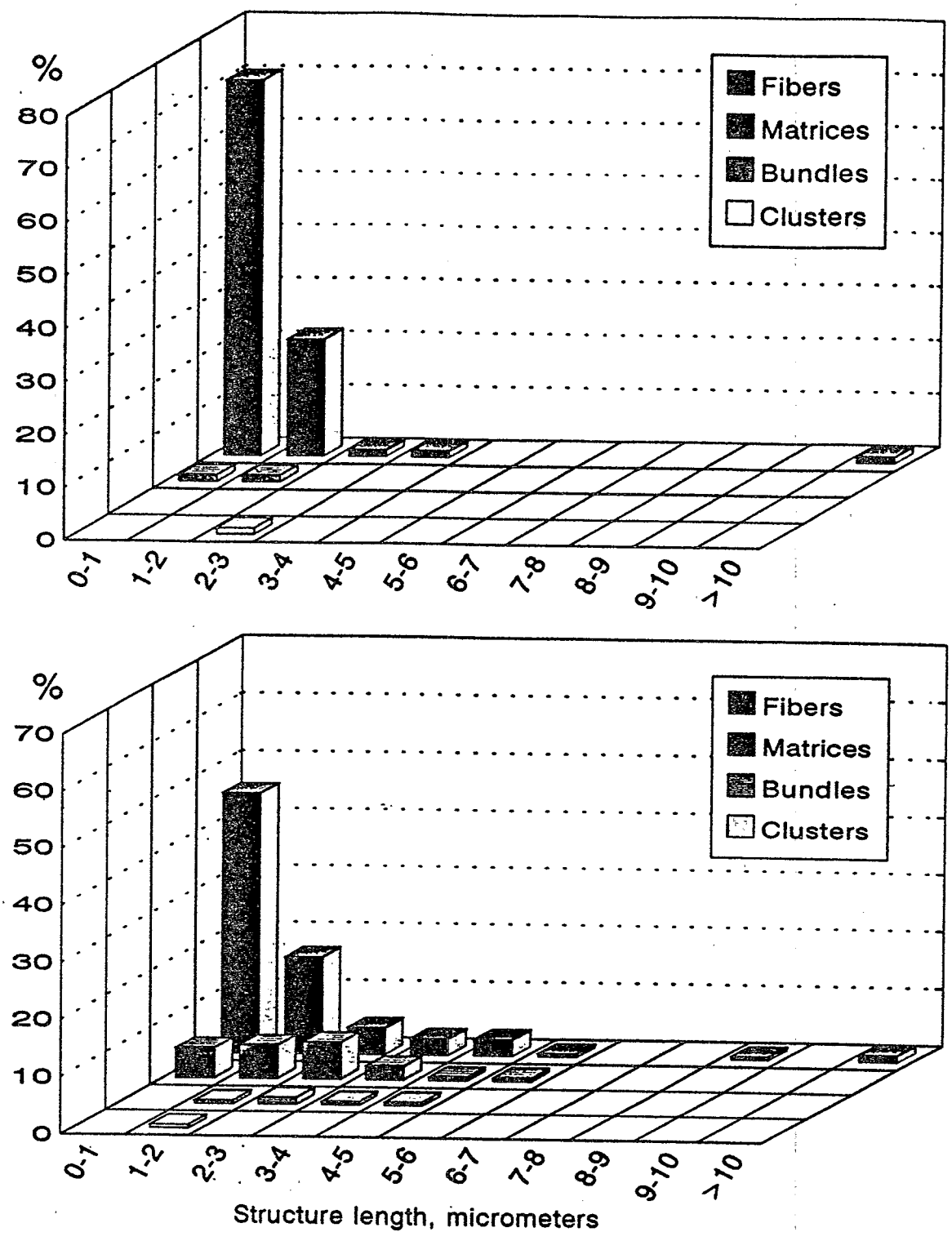

Figure J-4. Particle size distribution in area air before (top) and during (bottom) wet cleaning.

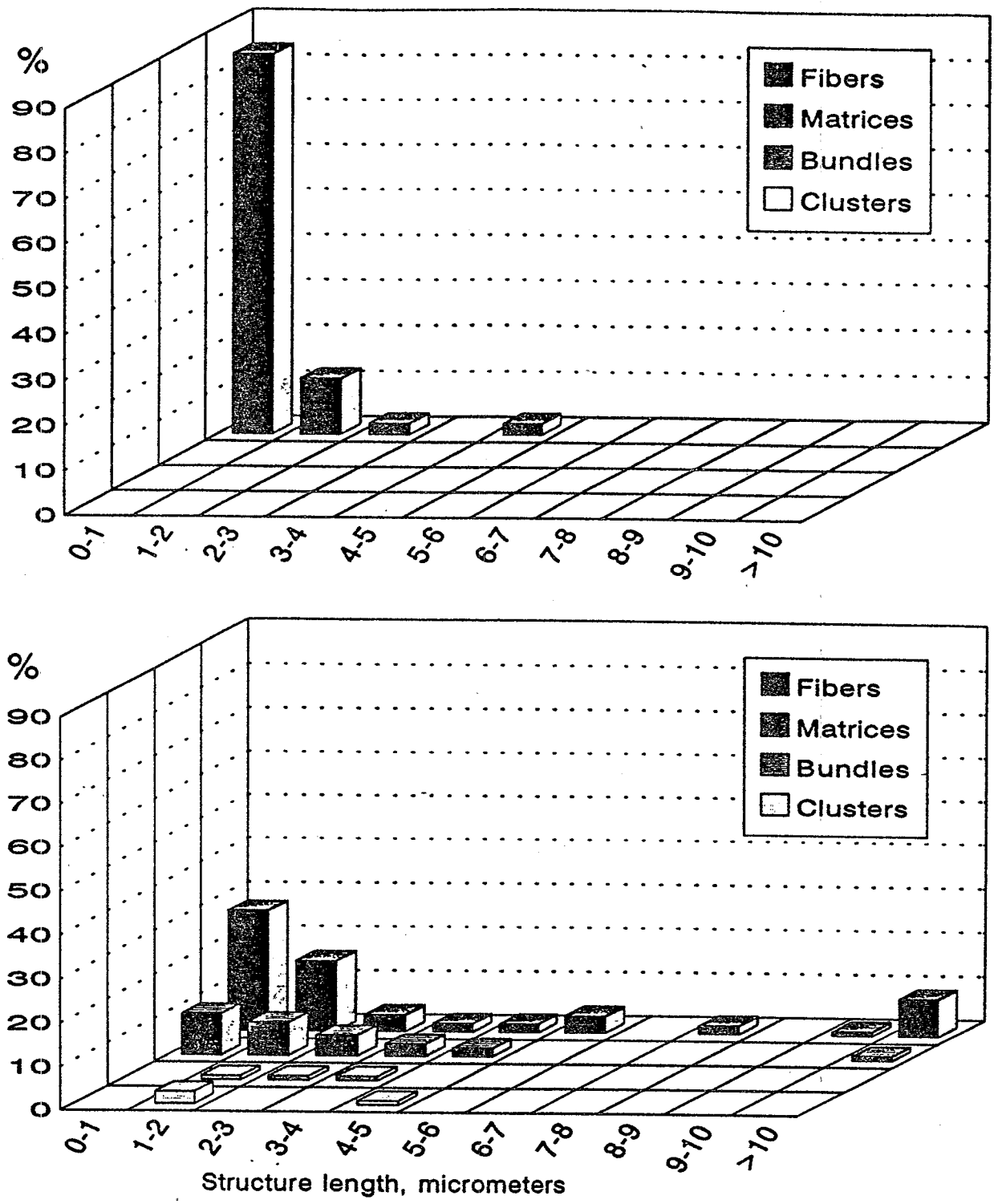

Figure J-6. Particle size distribution in area air before (top) and during removal of uncleaned carpet.